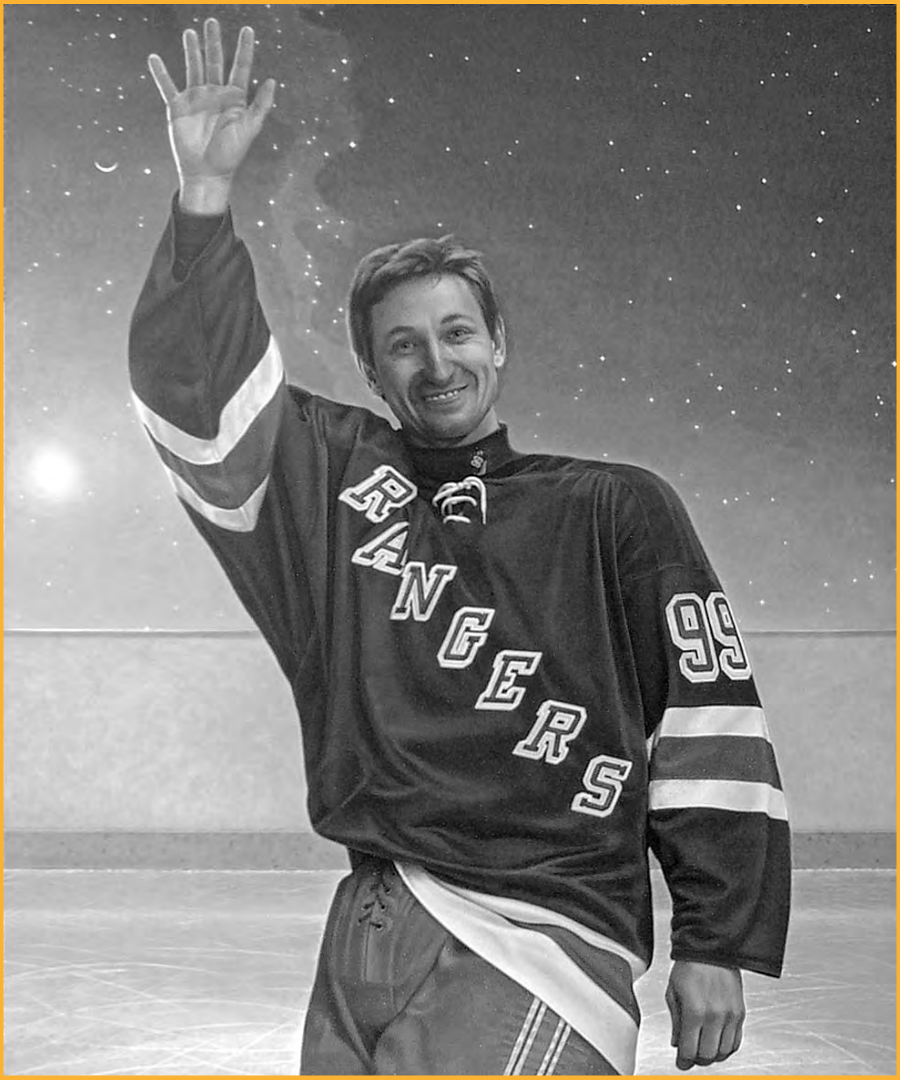
August/août 2004 Volume/volume 98 Number/numéro 4 [707]

Journal

The Journal of the Royal Astronomical Society of Canada Le Journal de la Société royale d'astronomie du Canada



INSIDE THIS ISSUE

The Sky Behind Gretzky · Reflectance Laws and Planetary Photometry
The Spectrum of Light Pollution Over Guelph

August / août 2004

Journal

Vol. 98, No. 4 Whole Number 707

contents
table des matières

FEATURE ARTICLES/ARTICLES DE FOND

RESEARCH PAPERS/ARTICLES DE RECHERCHE

EDUCATION NOTES/ RUBRIQUES PÉDAGOGIQUES

COLUMNS/RUBRIQUES

Reflections
p. 154

A Moment With…
Dr. Philip Stooke
p. 172

DEPARTMENTS/DÉPARTEMENTS

News Notes
New Manitoba Meteorite
p. 145

2005 Observer's Calendar (see back cover)

ACROSS THE RASC
DU NOUVEAU DANS LES CENTRES

Cover:
The Sky Behind Gretzky
p. 147

Astrocryptic Answers
p. 176

1 T	I	2 R	I	3 O	N	■	4 C	5 I	R	6 C	L	7 E
H	■	E	■	R	■	8 O	■	N	■	H	■	L
9 U	R	A	N	I	U	M	■	10 D	R	A	C	O
N	■	L	■	O	■	I	■	I	■	R	■	G
11 D	E	M	O	N	■	12 C	L	A	V	I	U	S
E	■	■	■	I	■	R	■	■	■	O	■	■
13 R	U	14 P	E	S	■	O	■	15 C	E	T	U	16 S
■	■	E	■	■	■	N	■	A	■	■	■	I
17 M	E	T	O	18 N	I	C	■	19 L	Y	20 M	A	N
E	■	Z	■	U	■	E	■	O	■	O	■	N
21 R	A	V	E	N	■	22 T	O	R	O	N	T	O
A	■	A	■	K	■	I	■	I	■	G	■	T
23 K	E	L	V	I	N	■	24 A	S	C	E	N	T

President's Corner

by Rajiv Gupta (gupta@interchange.ubc.ca)

This column marks the end of my two-year term as President — by the time you read this column, I will be approximately two months into my "retirement." Retiring Presidents typically have served six years on the Executive, two each as second Vice-President, first Vice-President, and finally President, but my four years as Treasurer before entering the presidential stream rounds my time up to ten years. So, I look back not only on my term as President but on my decade as a member of the Executive starting in 1994.

A lot has changed in the Society since 1994, and all, I think, for the better. For most members, the changes have been most evident in the bimonthly mailings received from the Society. The current *Journal*, an amalgamation of the previous *Journal* and *Bulletin* into a single coherent and professionally designed publication, came into being in 1997. A key player in the revitalization of the *Journal*, Dave Lane, is now joining the Executive as second Vice-President. Also in 1997, *SkyNews*, the popular Canadian magazine of astronomy, became a benefit of membership in the Society, the result of a favourable arrangement negotiated by then-president Doug George with the publishers of *SkyNews*. This arrangement also includes a half-page of advertising space for the Society in each issue of the magazine, an opportunity for the Society to receive wide exposure in the Canadian astronomical community.

Administratively, a major change occurred in the way membership fees were collected, with an efficient centralized regime of fee collection replacing the previous collection of fees by local Centres. Extensive revisions to the Society's bylaws, overseen by Michael Watson, were implemented to support this change. A sophisticated custom software package, the MPA system, capable of handling the many nuances of membership handling as well as the Society's considerable sales of publications, was purchased. This centralization, also conceived by Doug George, was brought to fruition in 1999 by his successor Randy Attwood.

As treasurer from 1994–1998, I was responsible for modernizing the Society's financial infrastructure, so that accurate financial reports reflecting the increased in-house activity could be produced. My task was made immeasurably easier in 1996, when Bonnie Bird, with her considerable experience in accounting software, was hired as Executive Secretary.

The few years following the 1997–1999 overhaul were mostly a time of consolidation and fine-tuning of the "new Society." The Society is still reaping the benefits of the restructuring;

Journal

The *Journal* is a bi-monthly publication of the Royal Astronomical Society of Canada and is devoted to the advancement of astronomy and allied sciences. It contains articles on Canadian astronomers and current activities of the RASC and its Centres, research and review papers by professional and amateur astronomers, and articles of a historical, biographical, or educational nature of general interest to the astronomical community. All contributions are welcome, but the editors reserve the right to edit material prior to publication. Research papers are reviewed prior to publication, and professional astronomers with institutional affiliations are asked to pay publication charges of $100 per page. Such charges are waived for RASC members who do not have access to professional funds as well as for solicited articles. Manuscripts and other submitted material may be in English or French, and should be sent to the Editor-in-Chief.

The *Journal of The Royal Astronomical Society of Canada* is published at an annual subscription rate of $80.00 by The Royal Astronomical Society of Canada. Membership, which includes the publications (for personal use), is open to anyone interested in astronomy. Annual fees for 2004, $44.00; life membership is $880. Applications for subscriptions to the *Journal* or membership in the RASC, and information on how to acquire back issues of the *Journal* can be obtained from:

The Royal Astronomical Society of Canada
136 Dupont Street
Toronto ON M5R 1V2, Canada
Internet: nationaloffice@rasc.ca
Web site: www.rasc.ca
Telephone: (416) 924-7973
Fax: (416) 924-2911

Canadian Publications Mail Registration No. 09818
Canada Post: Send address changes to 136 Dupont St, Toronto ON M5R 1V2
Canada Post Publication Agreement No. 40069313

We acknowledge the financial support of the Government of Canada, through the Publications Assistance Program (PAP), toward our mailing costs.

U.S. POSTMASTER: Send address changes to IMS of NY, PO Box 1518, Champlain NY 12919.
U.S. Periodicals Registration Number 010-751.
Periodicals postage paid at Champlain NY and additional mailing offices.

ISSN 0035-872X

for example the current membership of just under 5000 is 74% higher than it was in 1996, and the numbers are still growing steadily each year.

I see the establishment last year of standing Education and Observing Committees as an indication that with its infrastructure now in order, the Society is starting to actually *do* more astronomy. The Education Committee has overseen the production of a unique teacher's guide in astronomy, *Skyways,* authored by Halifax Centre member Mary Lou Whitehorne; the Observing Committee has established and is overseeing innovative new observing programs.

So, looking back on the past ten years, I leave the Executive knowing that the Society in 2004 is improved over the Society in 1994. I leave with a sense of satisfaction in the small part I may have played in these improvements. I leave with a sense of gratitude for having been given the privilege to lead such a special organization, one that is looked upon worldwide as the model for a national astronomy organization and which recently celebrated its Royal Centenary. I leave with a sense of good fortune that I've had such highly competent and dedicated individuals to work with, a few of whom I've named above. Even though I am, naturally, a bit tired now of the constant stream of administrative work (accompanied, I might mention, by sporadic bursts and the occasional fireball), I know I'll miss the people with whom I've been actively engaged in the work.

My retirement will not be a time of total disengagement from the Society since I will still be a member of National Council for the next four years, and my involvement as editor of the *Observer's Handbook* may last even longer. The freedom from the duties of President will open up considerable time for me to also do astronomy (in the form of astrophotography), as a proud member of a unique and thriving national organization called the Royal Astronomical Society of Canada.

Editorial

by Michael Allen (mlfa@wsu.edu)

In August of 2002 I took a position at Washington State University (WSU) at Pullman. I have one of an increasing number of hybrid positions: part-time university lecturer, and part-time education and public outreach (E/PO) professional. This type of work is a brainchild of the US, and there are lessons that Canadians can learn.

As an E/PO professional, I coordinate the Inland Northwest activities of Project ASTRO. Project ASTRO brings together astronomers and teachers as partners in learning. The task is a challenging one. In addition to having to become familiar with the US funding climate, there is also the education climate: there are science education standards at the national, state, and school district levels. In particular, I have to get to know the school districts very well. In the US there are over 8000 school districts, each with their own set of standards.

One of my most consuming tasks is recruiting. My original mindset was that finding teachers would be easy, and astronomers hard. Well, let me tell you, finding teachers is hard too. Teachers in Washington must continuously accumulate “clock hours,” which are similar to course credit hours. Although Project ASTRO offers clock hours, teachers have so many choices, and are so harried, that many overlook the program.

Couple the above with the population density in eastern Washington. Our program is the only rural site for Project ASTRO. Pullman itself has a population of 26,000, but of these, 17,000 are undergrads (it amuses me that 35,000 people come to the football games; during the autumn, the town completely changes its complexion every second Saturday). To make a long story short, I spend a lot of time stuffing envelopes and writing creative electronic mail, in an effort to get the word out.

I also regularly visit the local amateur astronomical societies, a task that I find very rewarding. The two most active, local societies are the Pullman-based Palouse Astronomical Society, and the Spokane Astronomical Society (SAS), located about 90 minutes north of Pullman. SAS meetings are a treat: about 100 people come to every meeting, there are interesting discussions, a group of dedicated telescope builders, and great door prizes! I have rather embarrassingly won twice in the last year, compared with another fellow who complained he had come to meetings for many years and has not won once!

Project ASTRO is administered by the Astronomical Society of the Pacific (ASP). The ASP is about to re-invent itself with the goal of becoming the leader in astronomy education.

In Canada, the Canadian Astronomical Society / Société Canadienne d’Astronomie (CASCA) and the RASC serve a similar purpose. As you flip through the pages of any recent issue of the *Journal*, you will find articles on history and education side-by-side with the Society’s news. This design is part of the vision of the Editor-in-Chief, Wayne Barkhouse. Under his leadership, the *Journal* continues to fill an important niche in the world of Canadian astronomy. Thanks, Wayne! The RASC leads the way in bringing astronomy to the public; collaboration with CASCA and local school boards can only enhance this outreach. A step in the right direction is Mary Lou Whitehorne’s recent publication, *Skyways*, an astronomy handbook for teachers.

I thoroughly enjoy being immersed in the E/PO environment. Not only do I supervise a number of successful teacher-astronomer partnerships, but I also get to visit the schools, science centres, and amateur organizations of rural Washington, and experience the wonder of people learning about the sky for the first time, or the hundredth time. I hope you enjoy such experiences as well, and wish you all clear skies!

ARE YOU MOVING? IS YOUR ADDRESS INCORRECT?

If you are planning to move, or your address is incorrect on the label of your *Journal*, please contact the National Office immediately:

(888) 924-7272 (in Canada)
(416) 924-7973 (outside Canada)
email: nationaloffice@rasc.ca

By changing your address in advance, you will continue to receive all issues of the *Journal* and *SkyNews*.

News Notes
En Manchettes

DR. HELEN SAWYER HOGG: DOUBLE HONOURS

The Canada Science and Technology Museum recently announced that three exceptional Canadian scientists, Helen Sawyer Hogg, Raymond Urgel Lemieux, and Sir John William Dawson will be inducted into the Canadian Science and Engineering Hall of Fame on May 20, 2004.

Housed at the Museum, the Canadian Science and Engineering Hall of Fame is a permanent exhibition that honours individuals whose outstanding scientific or technological achievements have had long-term implications for Canadians. A Web page about the Hall of Fame can be accessed at: `www.sciencetech.technomuses.ca.`

The Museum intends to display artifacts from its collection to show its visitors how the Hall of Fame Canadians have contributed to our everyday lives. Brief outlines of the most recent inductee's works are given below:

Helen Sawyer Hogg (1905-1993) took thousands of photographs of globular clusters to search for and study variable stars. She devoted herself to the popularization of astronomy by teaching elementary astronomy for non-science students and by writing a column that appeared in the Toronto Star for over thirty years.

Raymond Urgel Lemieux (1920-2000) brought the field of carbohydrate chemistry into the mainstream of organic chemistry and revealed how carbohydrates bind to proteins, a phenomenon crucial to everything from immunology to cancer.

Sir John William Dawson (1820-1899) was a geologist and educator of international reputation. Whenever we study fossils of plants we are building on his discoveries. Dawson was the first president of the Royal Society of Canada and the only person to have served as president of both the American Association for the Advancement of Science (AAAS) and the British Association for the Advancement of Science (BAAS).

There are currently 31 Canadian scientists and innovators recognized in the Hall of Fame, including Maude Abbot, Wilder Penfield, Sir Sandford Fleming, and Joseph Armand Bombardier. The achievements of these and the other members of the Hall of Fame have been so remarkable and their contributions to society so great that the Canada Science and Technology Museum hopes one day all Canadians will be aware of their accomplishments.

In addition to the Hall of Fame nomination, Dr. Helen Sawyer Hogg has also been honoured by the University of Toronto by being added to its ***Great Teaching*** Web site at `www.utoronto.ca/ota/GreatTeaching/index.htm.`

NEW MANITOBA METEORITE

Figure 1 – Derek Erstelle holding one of the new Manitoba meteorite fragments.

Two new iron meteorite fragments have been identified from Manitoba by the Prairie Meteorite Search, a national project run jointly by researchers at Campion College at the University of Regina, the University of Calgary, and the University of Western Ontario. The new finds come from near Bernic Lake, close to the eastern border of the province.

The Bernic Lake meteorite is the sixth meteorite to be recovered in Manitoba, and is the third Manitoba "find" to be identified by the Prairie Meteorite Search. Meteorites are broadly classified as being either "falls," corresponding to meteorites that were seen to fall to Earth, and "finds," which correspond to meteorites found serendipitously, but with unknown fall dates. The two fragments had masses of 5.5 and 4.3 kg apiece.

Mr. Derek Erstelle found the two meteorite fragments in scrubland located some half-hour drive northeast of Lac Du Bonnet, Man. in the fall of 2002. "I was surprised when I stumbled upon these two extra-heavy rocks about fifteen feet apart," says Erstelle. "I initially suspected they were meteorites — they looked so out of place." The two fragments show distinctive surface weathering indicative of their having fallen hundreds or even thousands of years ago. Erstelle cut a small piece from one of the fragments and sent it away for analysis. It was the identification of nickel in the cut specimen, by Dr. Alan Hildebrand at the University of Calgary, that confirmed the meteorite "find." Dr. Stephen Kissin at Lakehead University later performed a detailed analysis of the iron, and identified the meteorite as belonging to group of iron meteorites known as IAB. The presence of two distinct fragments so close together suggests that many meteorites may have fallen in the area.

The Prairie Meteorite Search field campaign locates meteorites by encouraging prairie farmers to have rocks identified that they suspect may be meteorites. The project consists of local publicity and visits by the searcher to towns to show meteorite specimens and to identify possible meteorites. The project relies on people having seen meteorites and the possibility of immediate identification to make discoveries.

THE 2004 C.S. BEALS AWARD

Professor E.R. Seaquist has been honoured by CASCA's prestigious biennial Carlyle S. Beals Award, which recognizes outstanding achievement in research. The award was established by the Canadian Astronomical Society (CASCA) in 1981 in recognition of the groundbreaking research of the late C.S. Beals. It is awarded to a Canadian astronomer, or an astronomer working in Canada, in recognition of outstanding achievement in research, either as a specific achievement or as a lifetime of innovative research. The recipient is invited to address the society at its annual meeting, which, this year, will be held at the University of Manitoba in Winnipeg.

Born in Vancouver, Ernest Seaquist obtained a B.A.Sc. in engineering physics from the University of British Columbia in 1961, and then a Ph.D. in astronomy from the University of Toronto in 1966. Shortly after, he began his academic career as an assistant professor at this institution, and gradually climbed all the steps to full professor in 1978. He served as chair of the Astronomy and Astrophysics Department at the University of Toronto as well as director of the David Dunlap Observatory from 1988 to 1999.

Professor Seaquist has had a long and distinguished career in the domain of radio astronomy. Until about 1990 he was primarily concerned with radio emission from stars undergoing stellar mass loss. One of his great achievements was to propose an original radio method for getting the mass-loss-rate of stars from their ionized outflows. Another highlight of his career was deciphering the structure of SS433 — a binary system in which two jets of matter are ejected at relativistic speed from one of the stars — using both radio and X-ray data.

For the past fifteen years, he has focused his research on radio emission from active galaxies, mainly gas and outflows in starburst galaxies. This type of galaxy is probably representative of processes that were more common during the early history of our Universe.

Over the years professor Seaquist has trained about two-dozen graduate students, some of whom are professors and scientific leaders in their field. He has also generously contributed his time on several national committees on the development and the future of astronomy in Canada. He served as CASCA's president from 1986 to 1988. He will be retiring on June 30, 2004, but intends to remain active in research as professor emeritus at University of Toronto.

THE 2004 PLASKETT MEDAL

Jo-Anne Brown (University of Calgary) has been awarded the 2004 Plaskett medal for presenting the most outstanding thesis at a Canadian University in astronomy or astrophysics during the past two calendar years. The award, consisting of a gold medal, is bestowed jointly by the Canadian Astronomical Society (CASCA) and the Royal Astronomical Society of Canada (RASC) in recognition of the pivotal role played by John Stanley Plaskett in the establishment of astrophysical research in Canada. The laureate is also invited to address one or the other of the sponsoring societies at their annual meetings and to prepare a review paper to be published in the *Journal of the Royal Astronomical Society of Canada*. This year, Dr. Brown will address the Canadian Astronomical Society at its annual meeting hosted by the University of Manitoba.

After graduating from the University of Alberta, Jo-Anne Brown completed her M.Sc. thesis in optical communications at Queen's University, under the supervision of John Cartledge. From late 1993 to mid 1996, she was a hardware designer at Bell Northern Research (now Nortel) in Ottawa. She then moved back west to pursue a Ph.D. in radio astronomy at the University of Calgary under the supervision of Professor Russ Taylor. In her doctoral thesis entitled *The Magnetic Field in the Outer Galaxy*, Jo-Anne Brown used data from the Canadian Galactic Plane Survey (`www.ras.ucalgary.ca/CGPS/`) to model the morphology of the magnetic field in our galaxy. One of the key results from her thesis is a map with a 10-fold increase in spatial resolution over any previous surveys.

The Sky Behind Gretzky

by Robert L. Brooks (rbrooks@uoguelph.ca)

In May of 2001, the official portrait of Wayne Gretzky by Ken Danby was released. The background shows an image of the sky as it appeared at the moment that Gretzky left the ice. It is almost certainly the most accurate, purely artistic rendition of the night sky ever attempted. The author played a small role to help make it so and this is the story of how that came about.

The email message read that a telephone call had come in from Larry Humphries at Ken Danby Studios. Would I return the call? What's this all about, I thought, as I picked up the phone. I knew that Danby was a famous artist who had painted a number of hockey-related works but was probably the only person in Guelph who didn't know that he lived outside the city in a restored stone mill. It was late summer of 2000 and Larry explained that Ken Danby was working on an official retirement portrait of Wayne Gretzky and wanted to portray the sky as it appeared at the moment that the Great One left the ice. Larry had produced a chart of the sky as seen from Madison Square Garden and was wondering if I would be willing to help ensure the correctness of what they were doing.

Now there are no astronomers at the University of Guelph but there is a small observatory, there are two astronomy courses offered regularly, and there is the infrequent offering of an astrophysical topics course to senior students. I teach the latter, have taught one of the former, and am the astronomy club coordinator, so when phone calls like Larry's come in, they land on my desk. I smiled at the thought that some of my best friends are artists. How would Ken or Larry know that they are poets and musicians? Sure, I'd be willing to help.

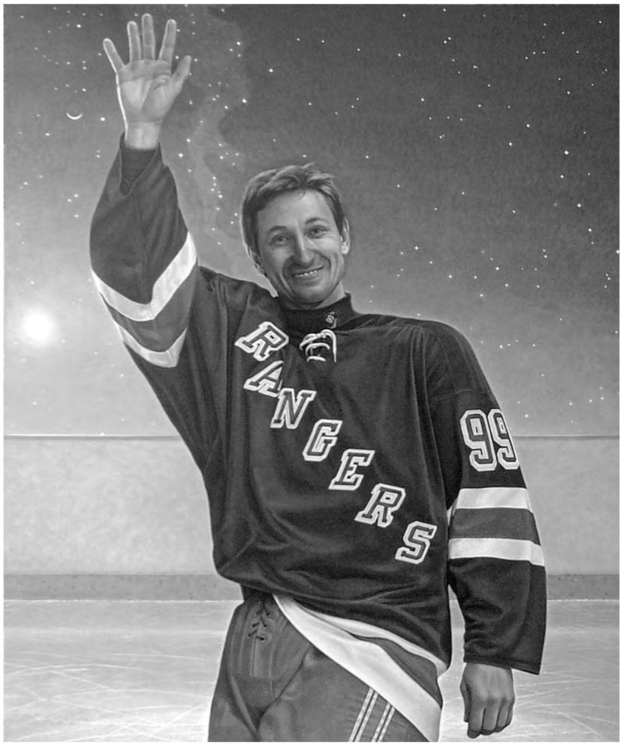


Figure 1 – The Great Farewell. Copyright Ken Danby 2001. Used with permission.

Before I knew it, we had arranged an appointment in my office for the three of us to look over what was being done. Larry had produced a chart of the sky using *Starry Night* and the outline of a waving figure was superimposed on the chart. In preparation for the meeting I had prepared my own chart of the sky using two different programs, one the professional version of what they were using. Now Danby is known for attention to detail. He is a realist painter. Going into the meeting I knew that the Sun was shining at the time Gretzky made his farewell and thought it a bit strange that one could see the stars without being in orbit. Anyone who has used a computerized sky chart knows that the Sun's presence is irrelevant, and besides, no one can see the sky from inside Madison Square Garden anyway, so I was getting into it.

My hardest task was to try to explain map projections and the fact that using a 130° field of view caused a lot of distortion. The sky would look different, using two different programs, if their projection algorithms were different. Also, I pointed out, such a wide field would include substantially more than the human eye would see from the bleachers if the walls were torn down, the Sun wasn't shining, the sky was clear, and there was a blackout in the city. The two of them stared at me. OK, I get it, I said.

In fact, Larry had done his homework and I could find nothing wrong with what they were trying to do. They explained that a small book would be distributed with the reproductions, that there would be a section in the book describing the astronomical aspects of the painting, and that they would appreciate it if I would proofread that section when it was finished (see `www.kendanby.ca`). "Of course", I replied.

In December I received an email saying that the book would soon be ready but that there was a question they would like answered. Is there ever a time when the positions of the planets and stars are repeated? They wanted to be able to claim that the positioning as portrayed at the exact moment that Gretzky left the ice was unique. Of course, I put on my professor's cap and wrote them 30 lines and five paragraphs, but if they read carefully they noticed the line, "In a nutshell, every night is unique. The stars and the planets never come back to the same positions when viewed from a given place...." I was thinking of all of the planets out to Pluto and all of the moons as well. For their pattern to repeat, I estimated it would take much longer than the age of the universe. I was lying in bed shortly thereafter thinking that the correct problem would be to ask if the stars and planets that were displayed on the painting would ever return to the positions as painted when viewed from New York. Given that the Sun and Moon are present, that Venus, Jupiter, and Saturn are present, and that Mercury and Mars are absent, it would take a long time before they matched the alignment to the precision of the painting. But the more uncertainty you allow in position, however, the shorter the time before the pattern repeats. The Big Dipper will look noticeably different in 100,000 years because of proper motion, and another back-of-the-envelope calculation convinced me that my statement is true, even allowing for the wide field of view and the width of the painter's brush.

It was February before I heard from them again. The painting was nearly completed, the book was ready to go to the printer, and they could send me the proofs of the astronomy section right away. The section was titled, "Mathematics, Astronomy and Curious Coincidences." Oh oh, I thought, I'm in for it — numerology! Now I know enough about the artistic soul to know that statistics is more foreign than ancient Greek. They were using the word "coincidences," which was fine, and what may be curious to one person can be shrugged off by another. Just let them stay this side of crazy, I thought, and I won't mind having my name acknowledged. I got past the part of adding dimensions that summed to 99, but then I read that Sirius, the brightest star in the sky, was visible and I couldn't for the life of me see how Sirius could be in a painting whose background faced north. There were a few other minor mistakes or stretches of fact and a lot of description about a painting I had not seen. I probably got up on the wrong side of the bed that morning, because I interpreted their acknowledgment to me as guaranteeing the correctness of every painted star, which on rereading it subsequently, it did not. I sent off an almost rude reply, suggested some corrections, rewrote the acknowledgment, and said that if they wanted a stronger statement then I would have to see the painting.

Now I don't know much about artists, the canvas, and brush type, but I know enough to know that who sees a major work of art, and when, is something carefully controlled by the artist, his muses, and the court astrologer. My chances of seeing the painting were almost non-existent so I put it out of my mind. A week or so later I received a phone call from Larry saying that Ken would like me to see the painting. I would be only the second person outside of the artist to see it and that he, Larry, would see it for the first time with me. I was ushered into the studio and there on the easel was *The Great Farewell*. It was an extraordinary moment for me. I have walked into the control rooms and storage ring tunnels of some of the largest accelerators on earth, barked commands from the bridge of a US naval warship, watched data pour in from an experiment 18 months in the planning, but never have a felt the kind of awe that filled me as I looked at that painting. I'm not even a fan of Gretzky and I can't skate. I probably muttered something about it being beautiful and while coffee was poured for the three of us I looked carefully at the sky behind because that was the reason I was there. How much could be changed if something was amiss? How much could I say?

The disk of the Sun is in the lower left and just above is the crescent Moon. Ken told me that he had painted the illuminated portion of the Moon the way the computer program had drawn it but after looking at the result realized that the illumination was not coming from the Sun! The distortion I warned them about produced such an effect but Ken had fixed that before I saw it. I wondered later if I would have noticed that myself. I smiled and said that I was looking at the Little Dipper for the first time. That wasn't quite true as my son pointed it out to me the previous summer while under a dark sky. I have seen Andromeda, the Coathanger, and any number of Messier objects but the Little Dipper just doesn't stand out because of the large contrast in brightness among the stars. Naked eye stars span about six magnitudes or a factor of about 250 in brightness. How do you do that on a painting? I offered no suggestions while present and it was over 30 minutes before I left the studio. On the drive back to my office I thought about the brightness problem and that both Venus and Jupiter were not as stunning as they should be. I drafted an email working out just how much brighter Venus was than the north star and similarly for Jupiter. A couple of days later Ken replied that he had made them brighter and dimmed the stars in the Little Dipper and was pleased with the result.

I know that the relative brightness of the stars in the painting is not exact - that if the background is 130° and the disk of the Sun and Moon are 0.5°, that they are much larger than "correct." These are matters of artistic license. Are there errors on the painting? I dare say that many of the readers of this journal would be more qualified than I to have played the role of advising astronomer. There may be errors I didn't catch but Ken Danby has artistically portrayed the night sky with a fidelity never before attempted. That he would care enough to consult a physics professor, whom he had never met, impressed me a lot. Besides, it was fun.

Robert L. Brooks is professor of Physics at the University of Guelph. He specializes in experimental atomic, molecular, and optical physics but also teaches astronomy and is the astronomy club coordinator.

On Reflectance Laws and the Theory of Planetary Photometry

by Maxwell B. Fairbairn (mbfairbairn@hotmail.com)

Introduction

Descriptions and derivations of reflectance rules used in the theory of planetary photometry are to be found scattered throughout the literature. The author has noted a strong inconsistency in the symbols and nomenclature used, as well as, in many cases, a lamentable lack of specification of the units used, so much so that quite some effort is required to reconcile work on this subject among different authors. The aim of this article is to gather all the analytical reflectance rules used and to present them in one place in a consistent manner, in particular by referring them all to a *bidirectional reflectance distribution function.*

Also presented are a table of reflectance functions for the calculation of model asteroid lightcurves and phase curves, and a set of equations that allow the calculation of Bond and geometrical albedos and the phase integral for any reflectance law that depends on solar phase angle and a possible set of reflectance parameters.

Symbols, Units, and Nomenclature

For the most part, the symbols, units, and nomenclature used here (Table I) are those used by Lester, McCall, & Tatum (1979), hereafter LMT, except that the quantity γ has been replaced by expressions involving ω_0, the *single scattering albedo,* $0 \leq \varpi_0 \leq 1$, (Chandrasekhar 1960). For the cosines of the angles of incidence and reflection (emergence) the symbols μ_0 and μ respectively are used, as is common in much of the literature.

The Bidirectional Reflectance Distribution Function (BRDF)

The BRDF (Nicodemus 1965, 1970) links the irradiance of a surface to the observed radiance in a given direction,

$$L = f_r E. \qquad (1)$$

As such, the BRDF is a function of the direction of the incident radiation and the direction of the reflected radiation. For the purposes of planetary photometry described here it may be regarded as a function of the cosine of the angle of incidence θ_i, the angle between the surface normal and the direction of incident radiation, $\mu_0 = \cos\theta_i$, and the cosine of the angle of reflection θ_r, the angle between the surface normal and the direction of the observer, $\mu = \cos\theta$ (although in certain cases it may be independent of one or both). It may also depend on the solar phase angle, or a list of parameters that accompany a reflectance rule, so that in general $f_r = f_r(\mu_0, \mu, ...)$

TABLE I.

Quantity	Synonyms	Symbol	SI Units
Radiant Flux	Radiant Power	P	W
Radiant Flux Density		F	$\mathrm{W \cdot m^{-2}}$
Irradiance		E	$\mathrm{W \cdot m^{-2}}$
Exitance	Emittance		$\mathrm{W \cdot m^{-2}}$
Radiance	Surface Brightness Specific Intensity	L	$\mathrm{W \cdot m^{-2} sr^{-1}}$
Intensity	Integrated Brightness	I	$\mathrm{W \cdot sr^{-1}}$
BRDF		f_r	$\mathrm{sr^{-1}}$

For a planet irradiated with a radiant flux density F, the irradiance is $E = F\mu_0$, where F is defined only for a plane parallel beam.

Lambert's Law

A Lambertian surface reflects its irradiance into the hemisphere from which it is irradiated so that the surface appears equally bright from whichever direction it is observed, *i.e.* its radiance is isotropic. By integrating the radiance over the hemisphere the exitance[1] is $M = \pi L$ and $\rho = \dfrac{M}{E}$ is the *directional hemispherical reflectance* (also *hemispherical albedo*), which cannot exceed unity, so that the maximum possible value of f is $\dfrac{1}{\pi}$ and the BRDF is thus,

$$f_r = \frac{\varpi_0}{\pi}. \qquad (2)$$

Lommel-Seeliger Law

This is a single scattering model based on the incident radiation being absorbed exponentially and radiated isotropically. The BRDF is

$$f_r = \frac{\varpi_0}{2\pi} \frac{1}{\mu_0 + \mu}. \qquad (3)$$

---

[1] The reader may be tempted to think that the result should be $M = 2\pi L$, after all there are 2π steradians in a hemisphere, but that is not the case. In M the "per square metre" refers to actual physical area, whereas in L it refers to *projected* area in the line of sight of the observer.

For a derivation of this law, see *e.g.* Hapke (1981).

Area Law

Often referred to in the literature as *geometric scattering,* the area law surface appears uniformly bright from whichever direction it is observed, whatever its shape, such that its radiance is proportional to the radiant flux density whatever the direction of the incident radiation, so that

$$f_r = \frac{\varpi_0}{\pi\mu_0}, \qquad (4)$$

from which it should be clear that no real object could obey such a law for all angles of incidence. Nevertheless, the area law has proved useful in the past as a first approximation and is still in use today. Put in its simplest terms, the law states that the intensity of the surface is proportional to the projected area presented to the observer, hence the terms "area" and "geometric."

Following LMT, we summarise the properties of the surfaces considered so far in the following table in which $p_n = \pi f_r(\mu_0 = \mu = 1)$ is the *normal albedo.*

Table II.

PROPERTIES OF SURFACES			
	Lambertian	Lommel-Seeliger	Area law
f_r	$\frac{\varpi_0}{\pi}$	$\frac{\varpi_0}{2\pi}\frac{1}{\mu_0+\mu}$	$\frac{\varpi_0}{\pi\mu_0}$
ρ	ϖ_0	$\varpi_0[1-\mu_0\ln(1+\frac{1}{\mu_0})]$	$\frac{\varpi_0}{\mu_0}$
p_n	ϖ_0	$\frac{\varpi_0}{4}$	ϖ_0

Spheres

The theory of planetary photometry can be considerably simplified for planets, which are well approximated by spheres. Again following LMT, we summarize properties of spheres, where q is the *phase integral,* p is the *geometrical albedo* (also *physical albedo*), and A is the *Bond albedo,* the three being related by $A=pq$.

Table III.

PROPERTIES OF SPHERES			
	Lambertian	Lommel-Seeliger	Area law
q	$\frac{3}{2}$	$\frac{16}{3}(1-\ln 2)$	2
p	$\frac{2\varpi_0}{3}$	$\frac{\varpi_0}{4}$	ϖ_o
A	ϖ_o	$\frac{4}{3}\varpi_0(1-\ln 2)$	$2\varpi_o$

Thus for a Lambertian sphere the Bond albedo and the single scattering albedo are the same thing, as they would be for any surface that is potentially lossless, by definition of Bond albedo. For a Lommel-Seeliger sphere the maximum possible value of the Bond albedo is 0.4091, and a sphere obeying the area law could not possibly obey conservation of energy.

The Opposition Effect

The laws so far discussed do not display an opposition effect — a non-linear surge in intensity as the phase angle approaches zero from small phase angles, a feature common to all atmosphereless bodies observed in the solar system. The following two laws are, among other things, attempts to resolve that problem. Both theories combine single scattering radiation, which is reflected once before returning to the hemisphere from which it came, and multiple scattering radiation, which is reflected more than once.

The Lumme-Bowell Law

The description here has been adapted from that given by Karttunen (1989), which is in turn based on the work of Lumme & Bowell (1981). The BRDF is

$$f_r = \frac{\varpi_0}{4\pi}\frac{1}{\mu_0+\mu}(2\Phi_1+\Phi_M), \qquad (5)$$

where Φ_1 is the single scattering phase function, itself the product of three functions

$$\Phi_1 = \Phi_S\Phi_{HG}\Phi_R. \qquad (6)$$

Here Φ_S accounts for shadowing, and is approximated by

$$\Phi_S \approx \exp\left(\frac{-\sin\alpha}{0.636D+1.828\sin\alpha}\right), \qquad (7)$$

in which the parameter $0 \leq D \leq 1$, the *volume density,* is a measure of the porosity of the reflecting surface and α is the solar phase angle.

Φ_{HG} is the single scattering Henyey-Greenstein phase function given by

$$\Phi_{HG} = \frac{1-g^2}{(1+g^2+2g\cos\alpha)^{3/2}}, \qquad (8)$$

where g is the *asymmetry factor* $-1 \leq g \leq 1$, in which $g = 0$ implies isotropic scattering. Negative values indicate backscatter and positive values forward scatter.

Φ_R accounts for (microscopic) roughness, and involves two parameters; $\rho \geq o$ and $0 \leq q \leq 1$ for *roughness* and the *area covered by holes respectively, i.e.*

$$\Phi_R = \frac{1+(1-q)\xi}{1+\rho q\xi}, \qquad \xi = (\mu^2+\mu_0^2-2\mu_0\mu\cos\alpha)^{1/2}/\mu\mu_0. \qquad (9)$$

The phase function $\Phi_M = h(\mu_0)\, h(\mu) - 1$ accounts for multiple scattering, and for $\varpi_0 < 0.6$, values suitable for most planetary applications, is approximated by

$$h(\mu) = 1 + a_0 + a_1\mu^2 , \qquad (10)$$

$$\begin{aligned} a_0 = \varpi_0 [1.108 \exp(2.464 \,|\, g \,|^{5/2}) \\ -0.64 \varpi_0^2 \exp(3.296 \,|\, g \,|^{5/2})]^{-1} , \end{aligned} \qquad (11)$$

$$a_1 = \varpi_0 (-0.624 - 0.240 g - 0.25 g^2) . \qquad (12)$$

Thus the Lumme-Bowell law involves five parameters. For examples of lightcurves and phase curves generated by the Lumme-Bowell law, see Karttunen & Bowell (1989).

Hapke's Law

This involves parameters ϖ_0 the single scattering albedo, h the *opposition surge width*, and B_0 the *opposition surge amplitude*. The BRDF [2] is

$$\begin{aligned} f_r = \frac{\varpi_0}{4\pi} \frac{1}{\mu_0 + \mu} \{[1 + B(\alpha)] P(\alpha) + \\ H(\mu_0) H(\mu) - 1\} , \end{aligned} \qquad (13)$$

and the reader should recognize the similarity to the Lumme-Bowell theory. In equation (13) the first term inside the braces refers to single scattering and the remainder to multiple scattering, where H is approximated by

$$H(\mu) = \frac{1 + 2\mu}{1 + 2(1 - \varpi_0)^{1/2} \mu} , \qquad (14)$$

and the *backscattering function* is

$$\begin{aligned} B(\alpha) = B_0 \left[\begin{matrix} 1 - \dfrac{\tan|\alpha|}{2h} (3 - \exp(-h/\tan|\alpha|) \\ (1 - \exp(-h/\tan|\alpha|) \end{matrix} \right] , |\alpha| \le \pi/2 \\ B(\alpha) = 0, |\alpha| > \pi/2 \end{aligned} \qquad (15)$$

If B_0 is approximated by

$$B_0 \approx \exp(-\varpi_0^2/2), \qquad (16)$$

which Hapke (1981) suggests is a suitable approximation for planetary regoliths then the number of parameters may be reduced by one. There are, however, variants of $B(\alpha)$that allow B_0 to exceed unity; see *e.g.* Helfenstein & Veverka (1989).

The single particle phase function $P(\alpha)$ may be any phase function, so if we chose the Henyey-Greenstein function as with the Lumme-Bowell law, as is usually the case in practice, then the two laws share two common parameters, ϖ_0 and g.

Macroscopic Roughness

Hapke (1984) presents a theory to correct for macroscopic roughness which introduces a single parameter $\bar{\vartheta}$, the *average slope of macroscopic roughness* expressed in degrees. Although the author has only ever seen it used in conjunction with Hapke's Law, it is important to appreciate that this theory may be applied to *any* reflectance rule, so that one could consider, say, a macroscopically rough Lambertian sphere.

The equations needed are rather bulky and not presented here. Suffice it to say that, although bulky, the equations merely correct μ_0 and μ to new values μ'_0 and μ'.

Asteroid Lightcurves and Lightcurve Inversion

Model asteroid lightcurves are most efficiently calculated by approximating the surface as a set of connected triangular facets (Fairbairn 2003). The optimum method of triangulation is known as *octant triangulation* (Kaasalainen & Torppa 2001), in which typically N=512-800 facets are suitable to calculate to the accuracy of CCD photometry. For each facet of area ΔA the irradiance is $E = F\mu_0$ and the intensity is $\Delta I = f_r F \mu_0 \mu \Delta A$, where $\mu\Delta A$ is the projected area in the line of sight of the observer.

For a surface that is everywhere convex, the relative magnitude m, which determines the lightcurve profile, is then

$$m = -2.5 \log \sum_{k=1}^{N} \sigma(\mu_0, \mu, \alpha, ...) \Delta A_k , \mu_0 > 0, \mu > 0 . \qquad (17)$$

Here the condition $\mu_0 > 0$ and $\mu > 0$ is necessary for the facet of area ΔA_k to be both irradiated and not obscured from the observer. For non-convex surfaces, a ray-tracing algorithm must be employed. The reflectance functions $\sigma(\mu_0,\mu,\alpha,...)$ to be used are summarized in Table IV.

TABLE IV.

REFLECTANCE RULE	$\sigma(\mu_0, \mu, \alpha, ...)$
Area Law	μ
Lambert's Law	$\mu_0 \mu$
Lommel-Seeliger	$\dfrac{\mu_0 \mu}{\mu_0 + \mu}$
Lumme-Bowell	$\dfrac{\mu_0 \mu}{\mu_0 + \mu} (2\Phi_1 + \Phi_M)$
Hapke	$\dfrac{\mu_0 \mu}{\mu_0 + \mu} \{[1 + B(\alpha)] \Phi_{HG} + H(\mu_0) H(\mu) - 1\}$

In recent years, considerable success at lightcurve inversion has been achieved by adopting a hybrid scattering law, which is a weighted combination of the Lommel-Seeliger Law, to model single scattering, and Lambert's Law, to model multiple scattering (Kaasalainen, Mottola, & Fulchignoni 2003), so that

$$\sigma(\mu, \mu_0, \alpha) = f(\alpha) \mu_0 \mu \left(\frac{1}{\mu_0 + \mu} + c \right) , \qquad (18)$$

where the constant c is a weighting factor and the function $f(\alpha)$ is used to model the opposition effect

$$f(\alpha) = a \exp\left(-\frac{\alpha}{d} \right) + k\alpha + 1 , \qquad (19)$$

---

[2] In his original paper Hapke (1981) derives a *bidirectional reflectance function,* given the symbol **r**. It is not the same as the *bidirectional reflectance distribution function* f_r . The two are closely related, so that $\mathbf{r} = \mu_0 f_r$.

where *a* and *d* are the amplitude and scale length of the opposition effect, and *k* is the overall slope of the phase curve.

More Surfaces and Spheres

For the Lumme-Bowell law, it is easy to show that the normal albedo may be calculated from

$$p_n = \frac{\varpi_0}{8}\left(\frac{2(1-g)}{(1+g)^2} + h^2(\mu_0) - 1\right). \quad (20)$$

The author has found two definitions of normal albedo in the literature. In one, the surface must be radiated normally and observed normally ($\mu = \mu_0 = 1$) and the other, in which it can be irradiated from any direction, in which case p_n is a function of μ_0. A similar equation may be derived for Hapke's law.

In the case of his own theory, Hapke (1981) has calculated analytical expressions for normal albedo, the directional hemispherical reflectance, the Bond albedo, and the geometrical albedo through somewhat different notation and making certain assumptions and approximations on the way, and then calculated the phase integral from $q = A/p$.

In the following, we present equations that may be applied to *any* reflectance rule in which the BRDF is dependent on phase angle and a possible list of reflectance parameters, so that the BRDF can be expressed as $f_r(\mu_0,\mu,\alpha;...)$.

The directional hemispherical reflectance may be calculated from LMT, equation (4), expressed in the form

$$\rho(\mu_0) = \int_0^{2\pi}\int_0^{\pi/2} f_r(\mu_0,\mu,\alpha;...) \cos\theta_r \sin\theta_r d\theta_r d\phi_r. \quad (21)$$

In this integral, the phase angle is the angle between the incident and reflected radiation, and with the aid of a little vector analysis, to wit, a dot product, it can be shown that

$$\cos\alpha = \mu_0\mu + \sqrt{(1-\mu_0^2)(1-\mu^2)}\cos\phi_r, \quad (22)$$

so that

$$\rho(\mu_0) = \int_0^{2\pi}\int_0^1 f_r(\mu_0,\mu,\alpha;...)\mu d\mu d\phi_r. \quad (23)$$

This done, we can now proceed to calculate the Bond albedo, which is defined as the ratio of the total radiant flux P_r reflected by a sphere to the total radiant flux P_i intercepted by the sphere. If we consider a sphere of radius α centred at the origin of an *Oxyz* frame, with spherical coordinates (r,θ,ϕ), irradiated with radiant flux density *F* from the *z*-direction, the intercepted flux is $P_i = \pi a^2 F$, $\mu_0 = \cos\theta$, and the Bond albedo may be calculated from LMT, equation (40) such that

$$A = \frac{P_r}{P_i} = \frac{1}{\pi}\int_0^{2\pi}\int_0^{\pi/2} \rho(\cos\theta)\cos\theta\sin\theta d\theta d\phi, \quad (24)$$

resulting in

$$A = 2\int_0^1 \rho(\mu)\mu d\mu. \quad (25)$$

Next, we need to determine the geometrical albedo, which compares the intensity of a sphere at full phase to the intensity of a likewise observed lossless Lambertian disc ($\varpi = 1$) of the same radius.

Again, if we consider a sphere of radius α centred at the origin, irradiated with radiant flux density *F* from the *z*-direction, then $\mu_0 = \mu = \cos\theta$, the intensity of the Lambertian disc is a^2F, and the geometrical albedo is then

$$p = \frac{I(\alpha = 0)}{a^2 F},$$

and using LMT, equation (29) we find that

$$p = \int_0^{2\pi}\int_0^{\pi/2} f_r(\cos\theta)\cos^2\theta\sin\theta d\theta d\phi, \quad (26)$$

hence

$$p = 2\pi\int_0^1 f_r(\mu)\mu^2 d\mu. \quad (27)$$

The phase integral can be determined by dividing equation (25) by equation (27), and also can, and should, be calculated independently of *A* and *p*, in order to check that $A = pq$ holds. The phase integral is

$$q = 2\int_0^{\pi} \psi(\alpha)\sin\alpha d\alpha, \quad (28)$$

where the *phase function* is

$$\psi(\alpha) = I(\alpha)/I(0), \quad (29)$$

the ratio of the intensity of the sphere at phase α to that at full phase. $\psi(\alpha)$ may be calculated from LMT equations (30), (32), and (34) such that

$$I(\alpha) = \int_{\alpha-\pi/2}^{\pi/2}\int_0^{\pi} f_r(\mu_0,\mu,\alpha;...) \sin^3\theta\cos\phi\cos(\alpha-\phi)d\theta d\phi. \quad (30)$$

where $\mu_0 = \sin\theta\cos\theta$ and $\mu = \sin\theta\cos\theta(\alpha\text{-}\phi)$.

Concluding Remarks

It is hoped that this article will prove to be useful to some readers. For example, the contents of Table IV would allow a consistent comparative study of lightcurves and phase curves under different reflectance rules. Using appropriate methods, equations (21)-(30) can be quickly and accurately evaluated numerically (see the example in the Appendix), obviating the need to derive analytical expressions that may involve further approximations to those already contained in the theory.

REFERENCES

Bowell, E., Hapke B., Domingue, D., Lumme, K., Petltonieme, J., & Harris,W. 1989, in Asteroids II, ed. R.P. Binzel, T. Gehrels, & M.S. Matthews (University of Arizona Press: Tucson), 524
Chandrasekhar, S. 1960, Radiative Transfer (Dover: New York)
Fairbairn, M.B. 2003, JRASC, 97, 232
Hapke, B. 1981, J. Geophys. Res., 86, 3039
Hapke, B. 1984, Icarus, 59, 41
Helfenstein, P., & Veverka, J. 1989, in Asteroids II, ed. R.P. Binzel, T. Gehrels, & M.S. Matthews University of Arizona Press: Tucson), 557
Kaasalainen, M., & Torppa, J. 2001, Icarus, 153, 24

Kaasalainen, M., Torppa, J., & Muinonen, K. 2001, Icarus, 153, 37
Kaasalainen, M., Mottola, S., & Fulchignoni, M. 2003, in Asteroids III, ed. W.F. Bottke, A. Cellino, P. Paolicchi, & P. Binzel (University of Arizona Press: Tucson), 139
Karttunen, H. 1989, A&A, 208, 314
Karttunen, H., & Bowell, E. 1989, A&A, 208, 320
Lester, T.P., McCall, M.L., & Tatum, J.B. 1979, JRASC, 73, 233
Lumme, K., & Bowell, E. 1981, AJ, 86, 1694
Nicodemus, F.E. 1965, Appl. Opt., 4, 767
Nicodemus, F.E. 1970, Appl. Opt., 9, 1474

Appendix: A Numerical Example

Here we will keep it simple and consider an isotropic (g = 0) Hapke sphere with ϖ_0 = 0.5 and an opposition surge amplitude B_0 determined by equation (16) and opposition surge widths in the range h = 0.1-1.4, these values being typical of surfaces containing an abundance of fine particles. In this case the BRDF is a function of three variables and just two parameters,

$$f_r(\mu_0,\mu,\alpha;\varpi_0,h) = \frac{\varpi_0}{4\pi}\frac{[B(\alpha)+H(\mu_0)H(\mu)]}{\mu_0+\mu}\,. \qquad (31)$$

The phase function is shown in Figure 1, for the case h = 0.2 (in bold) with the Lommel-Seeliger phase function shown for comparison. The opposition effect is clearly apparent.

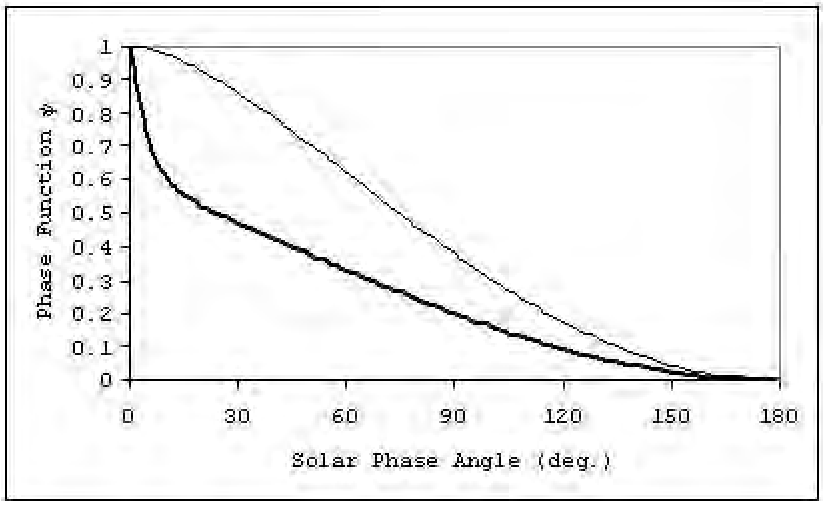


Figure 1

The geometrical albedo is

$$p = \frac{\varpi_0}{4}\int_0^1 [B_0 + H^2(\mu)]\mu d\mu\,, \qquad (32)$$

so that the value of p will be independent of the opposition surge width. Results are summarized in Table V.

Table V

h	0.1	0.2	0.3	0.4
p	0.14431	0.14431	0.14431	0.14431
A	0.14376	0.14494	0.14632	0.14777
q	0.99596	1.00427	1.01388	1.02396
A/q	0.14434	0.14433	0.14432	0.14432

In this table, it can be seen that the value of p remains constant and is very close to the value of A/q (less than ~0.02% difference). All results were computed numerically and the discrepancy can be attributed to accumulated errors for the Bond albedo and the phase integral, which are both triple integrals; p is just a single integral and can be computed very accurately and quickly. The results shown were obtained using Gauss-Legendre quadrature (16-point), which, in the author's experience, is difficult to understand, easy to program, delightfully fast, and astonishingly accurate.

Knowledge of the geometrical albedo allows the calculation of the diameter D of the spherical equivalent of an unresolved asteroid (and vice-versa for a resolved asteroid). In the HG magnitude system (Bowell *et al.* 1989) the absolute visual magnitude H and the visual geometrical albedo p_v are related by the equation

$$\log p_v = 6.259 - 2\log D - 0.4H\,, \qquad (33)$$

where the diameter D is in km. For the example presented here and, say, H = 15.0, the resulting diameter is D = 3.55 km. ◆

Max Fairbairn completed his M.Sc. in Astrophysics at the University of Victoria, B.C., in 1972. Since then he has taught Physics and Computer Programming at various tertiary institutions. He lives near Sydney, Australia.

The Hulse-Taylor Binary Pulsar (1974)

by David M.F. Chapman (dave.chapman@ns.sympatico.ca)

Thirty years ago a keen 23-year-old astrophysics graduate student named Russell Hulse was poring over his radio-telescope data from pulsar PSR 1913+16 and concluded that he and his supervisor Joseph Taylor had discovered a new type of object: a binary pulsar. The pulsar — a type of neutron star — was spinning at a rate of 17 times per second, emitting pulses of radio waves 59 milliseconds apart. On top of that, the pulsar had a "wobble" in its pulsation period that could only be explained if the pulsar were one of a pair of objects orbiting each other. The Hulse-Taylor object PSR 1913+16 (whose name provides its approximate position in the sky) was discovered to be binary in September 1974 using the 305-m Arecibo radio telescope in Puerto Rico, and continued observations of the object provided data that verified several predictions of Albert Einstein's general theory of relativity. For their work, Hulse and Taylor were awarded the Nobel Prize in Physics in 1993.

The People

Joseph Hooton Taylor was born to Quaker parents on March 29, 1941, in Philadelphia, Pennsylvania. He and his brother became involved in ham radio at an early age, constructing large steerable antennas and scavenging parts from old TVs. Taylor put together a radio telescope as a high school project. Taylor received a B.A. from Haverford College, Pennsylvania in 1963 and went on to graduate work in astronomy at Harvard University, earning a doctorate in 1968. He was a professor at the University of Massachusetts at Amherst during the years 1969–1981. Now at Princeton University, Taylor continues to study pulsars (with much more powerful computers). His philosophy of scientific life is simple and direct:


Figure 1 – 1993 Nobel Laureate (Physics) Russell Hulse (1950 –).


Figure 2 – 1993 Nobel Laureate (Physics) Joseph Taylor (1942 –)

> "I have noticed in recent years that many budding scientists worry much more than I ever did about what the future may bring: how to get into the best university, work with the biggest names, find the best post-doctoral fellowship, and secure the ideal university position. My own psychological bent, insofar as it has influenced any professional decisions, is to pursue a path promising enjoyment along the way, without looking too far ahead. Perhaps related to my Quaker upbringing, I've always valued personal involvement in a difficult task over appeals to eminence or authority; I like the challenge of re-examining a problem from fresh perspectives. Ultimately, I believe that in important matters we are mostly self-taught, but in a way that is strongly reinforced by cooperative human relationships."

More information on Joseph Taylor can be found at `www.almaz.com/nobel/physics/1993b.html`.

Russell Alan Hulse was born on November 28, 1950, in The Bronx, New York City. He showed an unusual curiosity and interest in science as a boy. While still in high school (The Bronx High School of Science) he built a radio telescope. In many ways, his boyhood fascination with science echoed that of his future thesis supervisor, Joseph Taylor. He studied physics at Cooper Union College, from which he graduated in 1970. He developed an interest in FORTRAN programming and orbit simulations. As a graduate student at the University of Massachusetts at Amherst, he worked under Joseph Taylor, graduating with a doctorate in 1975. His thesis project on pulsars neatly

Figure 3 – Arecibo Observatory, Puerto Rico, used by Hulse and Taylor to study PSR 1913+16.

combined his interests in radio astronomy, computers, and celestial mechanics. Despite being a Nobel Laureate, Hulse was concerned that he could make a career out of astronomy, and switched fields from astrophysics to plasma physics by joining the Princeton Plasma Physics Laboratory in 1977. Russell Hulse has the following observations on life as a scientist:

"I do not pretend to be anything like an accomplished expert in all of the many things that I have ever been or am presently involved in doing. My most fundamental urge has always been just to spend time on what I found the most interesting, trying of course to match this up somehow with the more practical demands of life and a career. In this sense I have come to realize that at times I must not have always been the easiest person to have had as a student, or as an employee, and I therefore appreciate the efforts of those who helped me to accommodate myself to these practical demands, or often, who worked to help accommodate the practical demands to me."

More information on Russell Hulse can be found at `www.almaz.com/nobel/physics/1993b.html`.

The Physics

A pulsar is a rapidly spinning, highly magnetic, neutron star. The star emits radio waves in a narrow beam along the magnetic axis of the star. If the beam happens to point at the observer (*i.e.* someone on Earth) at some time during the star's rotation, then the observer will see a rapid succession of radio wave pulses synchronized with the star's rotation. In this way, the radiation received from a pulsar is similar to the flash from a lighthouse with a rotating beacon: the radiation is steady, but the observer intercepts it only periodically.

If the pulsar is one member of a binary system, then the radio wave source may approach and recede from the observer, depending on the orientation of the orbits. If so, then the period of the pulsar — which is normally rock-steady — will vary up and down, a consequence of the Doppler effect. (An approaching siren will sound higher in pitch than a siren at rest, while a receding siren will sound lower in pitch.) Hulse analyzed the period changes of PSR 1913+16 and compared them with his simulations: he concluded that the period of orbital motion of the binary pulsar is 7.75 hours, corresponding to the motion of two stars each of 1.4 solar mass in eccentric orbits with minimum separation of 1.1 solar radii and maximum separation of 4.8 solar radii. The orbital plane is inclined 45 degrees from our line of sight.

Because the binary pulsar experiences such a strong gravitational field, it is possible to observe effects in the data that are predicted by Einstein's general theory of relativity. For example, the orbit of the pulsar is highly eccentric, so the pulsar regularly dips deep into the gravitational well of its companion. There is an additional time delay in the arrival time of the pulses caused by time dilation in the strong gravitational field. Moreover, the orientation of the ellipse slowly rotates, another relativistic effect. The orbit of the pulsar rotates as much in a day as that of Mercury in a century! These observations were significant confirmations of the predictions of general relativity, especially as they were from an object outside the Solar System.

Following several years of observations, Hulse and Taylor noted that the orbital period of the binary pulsar was slowly decreasing: 76 millionths of a second per year, corresponding to a decrease in orbit size of 3.1 mm per orbit. This is attributed to loss of orbital energy by radiation of gravity waves. This phenomenon is also consistent with Einstein's theory, and the indirect observation of gravitational radiation by Hulse and Taylor provides much encouragement to projects that hope to directly observe gravitational waves, such as the Laser Interferometer Gravitational Wave Observatory (LIGO): `www.ligo.caltech.edu/`. ◆

David (Dave XVII) Chapman is a Life Member of the RASC and a past President of the Halifax Centre. By day, he is a Defence Scientist at Defence R&D Canada–Atlantic. Visit his astronomy page at `www3.ns.sympatico.ca/dave.chapman/astronomy_page.`

Unperturbed Procyon

by Leslie J. Sage (l.sage@naturedc.com)

Anyone who has played with a water balloon knows that when you touch its exterior, waves go through the water making the entire balloon jiggle. Basic physics dictates that the jiggling depends on just a few parameters, such as the density of water, size of the balloon, and the tension on its surface. In fact, accurate measurements of the waves can be used to calculate those parameters. Seismology is the analysis of waves transmitted through Earth, and helioseismology can be done for our Sun, where it has provided a lot of information about the interior structure of the Sun. Asteroseismology is the application of the same techniques to other stars, but technically it is exceedingly difficult to make the appropriate measurements from ground-based telescopes. Jaymie Matthews of the University of British Columbia and his collaborators have used Canada's first orbiting telescope — the Microvariability and Oscillations of STars (*MOST*) — to study the oscillations of Procyon, a third-magnitude F star about 11 light-years away (see the July 1, 2004 issue of *Nature*). This star has been regarded for 20 years as the best candidate for observing the kind of pressure-driven (p-mode) oscillations seen on the Sun, and indeed several claims of detections — based on ground-based measurements — have already been made. Surprisingly, Matthews and his colleagues see no oscillations anywhere near the expected level.

Physically, one can think of an oscillation like a pendulum. There is an equilibrium position (pendulum vertical), about which the pendulum oscillates when it is perturbed away from the equilibrium point. The restoring force is gravity, which wants to bring the pendulum back to the vertical position. The observed oscillations in our Sun are called p-modes because they arise from gas pressure, similar to sound waves in our atmosphere. The equilibrium point for the Sun is a perfect sphere.

Solar oscillations can be observed using photometry to measure changes in the brightness of a region on the surface, or with spectroscopy to measure the radial velocity of the gas. Changes in the brightness of a parcel of gas on the surface of the Sun are related to changes in velocity, because as the gas is compressed by a passing wave it is heated, while an expansion cools it slightly. The bulk displacement of the gas due to a wave is very small, but because the oscillations are weakly damped — they typically last several thousand cycles — their frequencies can be determined with relatively high precision. As the Sun appears quite large in the sky, compared to almost all other astronomical objects, its surface can be studied with very high spatial resolution. Millions of different modes of oscillation have been identified. (A mode is like an overtone of a fundamental in music.)

The surfaces of other stars (with just a few exceptions) cannot be resolved, so any oscillations will be averaged over the entire stellar disk. If the "horizontal wavelength" of the mode is much less than the radius of the star, to an observer on Earth the displacement (and therefore brightening) of the gas will average to zero. As a result, there are relatively few modes that could in principle be seen.

The *MOST* satellite was launched on June 30, 2003 into a polar orbit. The primary mirror has a diameter of 15 cm (much smaller than the *Hubble Space Telescope's* 2.4m), and the collected light goes to a CCD photometer. The photometer is very precise — it was designed to be able to measure variations of just a few parts per million, with the goal of detecting p-modes in Sun-like stars (and, hopefully, reflected light from planets orbiting those stars).

Stars like the Sun should behave similarly to the Sun. Procyon is an F5 VI-V star — the brightest in the constellation of Canis Minor (visible in the winter sky) — and has been thought to be one of the best targets for the observation of oscillations. In fact, there have been previous claims of detections, using ground-based observations. Because of this, and theoretical predictions about the oscillations, Procyon was the first science target (after the commissioning phase) for *MOST*.

Matthews and his collaborators collected 32 days of continuous data (with only minor gaps), but they see no evidence for p-mode oscillations in their data. They conclude that any oscillations that do exist must be smaller than 15 parts per million variation in the light and/or have lifetimes less than 2-3 days. So what about the earlier claims? Those were based on measurements of radial velocity variations in spectral line measurements. If they are correct, then the new *MOST* data will constrain quite tightly theories that relate the radial velocities and brightness variations. Or the earlier claims might be false, perhaps because the incomplete sampling introduced a spurious periodicity.

Planning further observations for the *MOST* mission, and for future missions designed to do asteroseismology, has now become a lot more complicated because the original plans were based on expectations about what would be seen from Procyon. It now appears that the earlier assumptions were incorrect. As is usual in science, the most interesting results are those that run counter to predictions! We can look forward to some more fascinating results from *MOST*. Meanwhile, we Canadians can look up into the sky and think about our own space telescope. ◉

Leslie J. Sage is Senior Editor, Physical Sciences, for Nature Magazine *and a Research Associate in the Astronomy Department at the University of Maryland. He grew up in Burlington, Ontario, where even the bright lights of Toronto did not dim his enthusiasm for astronomy. Currently he studies molecular gas and star formation in galaxies, particularly interacting ones.*

FROM THE PAST AU FIL DES ANS

LIGHT POLLUTION IN SOUTHERN ONTARIO

We have obtained data from visual and photoelectric instruments to define a population-brightness function for cities and a distance-brightness function for average atmospheric conditions in Ontario. We have used these functions to construct a simple mathematical model of light pollution in Ontario. Data from many locations indicate the model gives essentially correct results. We find, from direct observation and model calculations, that there are very few observing sites in southern Ontario unaffected by light pollution, and that these will degrade rapidly in the future. We fear that, within a few decades, there will be virtually no opportunity for anyone to view the natural sky in southern Ontario, which will be a great loss to our culture, as well as to astronomy and star-gazing.

by Richard L. Berry
from *Journal*, Vol. 70, p.97, June 1976.

THE SPECTRUM OF LIGHT POLLUTION OVER GUELPH

By Monique Ferguson and Robert L. Brooks

Department of Physics, University of Guelph
Electronic Mail: moferg9@yahoo.ca, rbrooks@uoguelph.ca

(Received September 7, 2003; revised April 5, 2004)

Abstract. The spectrum of the light pollution over Guelph has been measured from the University of Guelph's observatory using a research-level monochromator and sensitive photomultiplier. Spectra were acquired from 400 to 600 nm, pointing at two different areas of the surrounding city as well as for light reflected off of a uniform cloud cover. These spectra have been corrected for detector response and are compared to ones recently taken over Toronto. A quantitative estimate of the relevance of particular bands is made that could be of some use for the design of effective light-pollution filters.

Résumé. Le spectre de la pollution lumineuse au dessus de Guelph a été mesuré depuis l'observatoire de l'université de Guelph en utilisant un monochomateur de recherche et un photomultiplicateur sensible. Les spectres ont été recueuillis entre 400 et 600 nm, en pointant vers deux régions différentes de la ville environnante, aussi bien qu'à la lumière reflétante d'un ciel uniformément ennuagé. Ces spectres ont été corrigés pour tenir compte des réponses des détecteurs et ils ont été comparés aux spectres récemment captés au dessus de Toronto. Une estimation quantitative a été faite de la pertinance de certaines bandes qui pourrait servir à la conception de filtres efficaces contre la pollution lumineuse.

1. Introduction

Light pollution, the light from outdoor lighting that is scattered into the atmosphere and thence into the line of sight of telescopes, has long been recognized as a problem by astronomers but is now becoming recognized by a broader community (Mizon 2002; Thessin & Beatty 2002). With the incentive that the University of Guelph wants to replace the telescope in its roof-top observatory with a modern, albeit small, instrument, we faced the question of light pollution in trying to decide maximum useful aperture and wondered whether any filters were available that would significantly reduce adverse effects from surrounding city lights.

Whereas the sources of light pollution are known to be ubiquitous outdoor lighting, and the variety of such lights is also known, what is not so well known is the fraction of detected light in a given region of the 400 to 700 nm visible range that falls into the wavelength region dominated by the spectral line of some polluting source. Clearly such an assessment will be a local one depending on the lighting that predominates in the region surrounding the observatory. We wanted to see if we could make a measurement of the spectrum of the light pollution relevant for our own observatory and to see if there were filters on the market that might be of use (Markov 2001). There appear to be no published spectra of light pollution. One unpublished spectrum is remarkably similar to the one we measured, which led us to suspect that the light pollution over Guelph is probably quite similar to that over other cities in southern Ontario and possibly over others in North America.

Measuring the spectrum of light pollution is more difficult than might be expected because, despite seeming to be bright, in fact, it is not. Coupling a telescope to a good spectrometer, when neither was purchased for that purpose, is also difficult. Pointing any such telescope/spectrometer combination directly toward ground-based light sources (for comparison purposes) completes the challenge.

We shall present spectra we acquired from 400-600 nm of two different nearby sections of the city of Guelph and compare those to spectra taken from a fairly uniform cloud cover by pointing to a section of the sky above the centre of the city. After applying corrections for phototube response and even for Rayleigh scattering, we will present a table giving relative integrated intensities for each of the strongest spectral regions. Comparison to a recent spectrum acquired at the David Dunlop Observatory (DDO) in Toronto will be made (Rucinski 2002).[1]

2. Experimental Equipment

The observatory here consists of two 3.5-inch aperture *Questar*

---

[1] A spectrum of the Toronto sky was obtained on May 26/27, 2002 by Michael De Robertis, Robin Fingerhut, and Mel Blake of York University. Jim Thomson was the telescope operator.

telescopes mounted on pillars outside of the dome, which contains a 12-inch Newtonian reflector. Each of the two pillars is wired for standard 115 VAC. A 4-ft × 2-ft optical bread-board supported the spectrometer and photomultiplier tube while a second table supported the necessary electronics. Spectra were acquired using a 1/3-metre, scanning, grating monochromator (McPherson Model 218) with an EMI 9635QB photomultiplier tube (PMT) detector. Getting as much light as possible through the entrance slit of the monochromator was accomplished by using a 37-mm diameter lens (60-mm focal length) positioned inside a 48-cm long PVC tube as an optical collector. One end of the PVC tube was connected with a flexible light pipe to the entrance slit of the monochromator. The tube could be pointed toward light sources on the ground or toward the sky. When pointing directly toward city lights a few blocks away, there was sufficient light intensity to make measurements. This was not the case when pointing to the sky, so we devised a way to couple the open end of the PVC tube to the back of a 3.5-inch diameter *Questar* telescope thereby giving us significantly greater light gathering capability. In that way we had the option of pointing toward the sky (when connected to the *Questar*) or pointing just below the local horizon toward city lights. Even using the *Questar* telescope, there was insufficient light intensity scattered by a cloudless sky, so our sky measurements were made off clouds. Using the 12-inch telescope for this task would have required more physical alteration than we were prepared to invest.

Data acquisition was performed using a Stanford Instruments Photon Counter and personal computer running routines from our research laboratory. We chose the *Questar* positioned west of the dome, which afforded an unobstructed sight line toward the city centre.

One of the more unusual aspects of this experimental effort was that it was conducted outside in winter, being part of a senior undergraduate project. The monochromator was not designed to work at –10°C; the main screw seized, leading to a two-week delay in which we built an insulating box and placed a heating pad within it to keep the instrument functional.

The spectrometer had a dispersion of 2.2 nm per mm of slit width at a wavelength of 500-nm . Spectra were acquired using .04-mm slits for the ground spectra and 1-mm slits for the cloud spectra. The observed line widths are broader than the instrumental dispersion, which is caused by the convolution of the source line and the dispersion. The source lines are pressure broadened in many cases and are not isolated lines in others and our observed widths are consistent with these facts.

3. Results and Discussion

Figure 1 shows two spectra taken from nearby ground sources. The vertical scale for both is the same with an offset for visual clarity. Both were acquired on the same evening under identical conditions. The lower one was acquired while pointing toward a nearby parking lot with a preponderance of mercury lights, while the second one was acquired while pointing toward a brightly lit section of the city south of the university with a preponderance of sodium lamps. These spectra, and all subsequent spectra, have been corrected for the phototube response curve shown in the inset to Figure 1. Because of the poor response above 550 nm, quoted intensities above that value are not better than ±10%. The difference in these two spectra are striking - illustrating that light pollution differs from place to place.

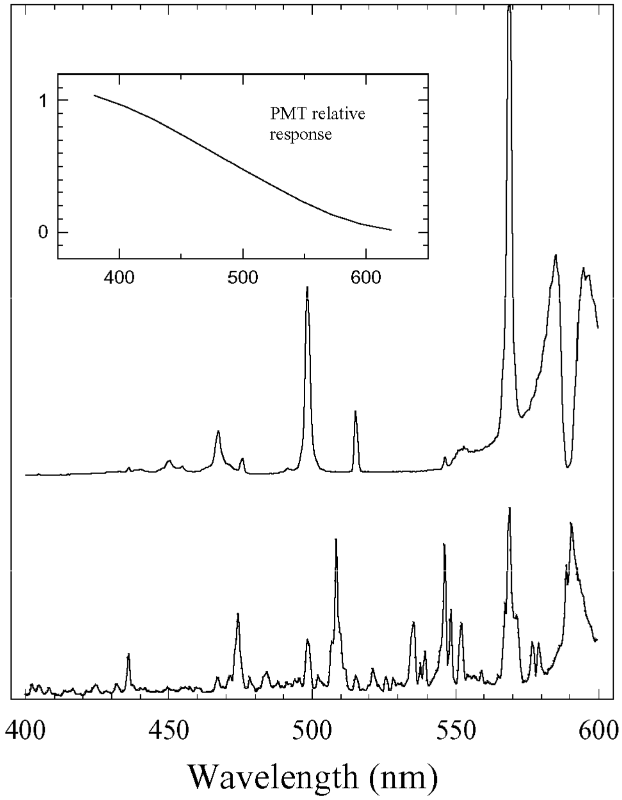


Figure 1 – Ground-pointing spectra acquired from two different sight lines in the vicinity of the Guelph observatory. Corrected for spectral response shown in the inset.

With the light tube connected to the back of one of the *Questar* telescopes, and with that telescope pointing to the clouds above the centre of Guelph, we acquired the spectra recorded on Figure 2. The slits were opened to 1 mm but the *Questar* simply does not have sufficient aperture to allow for a clear-sky measurement of light pollution. The three spectra were taken consecutively, without moving the telescope, and the lack of marked differences indicates the uniformity of the cloud cover on that night. (A break in the clouds over the approximately 40 minutes required for a spectrum would result in extremely reduced light intensity in the spectral region being scanned when the cloud break occurred.) Not surprisingly, the spectra are composed of the peaks observed in the ground-pointing spectra but it would have been impossible to guess the relative intensities of these peaks without making a cloud or sky measurement.

Given the desirability of having a single spectrum covering the full visual wavelength band, we have summed our three cloud spectra and pieced onto it the part of the curve above 600 nm obtained from the DDO unpublished result (see Figure 3). Furthermore, we have applied a λ^4 intensity scaling factor to our summed cloud spectrum by multiplying each datum by $600^4/\lambda^4$ with λ in nm. This correction applies the known wavelength dependence of Rayleigh scattering, which would be dominant when observing on a clear night, to our spectra acquired off the clouds. This recognizes that one only observes on a clear night and makes comparison with the DDO spectrum more reasonable. This should come close to duplicating what we would have measured on a clear dark night with a larger aperture telescope. The piece from 600-700 nm is shown using a dashed curve. This

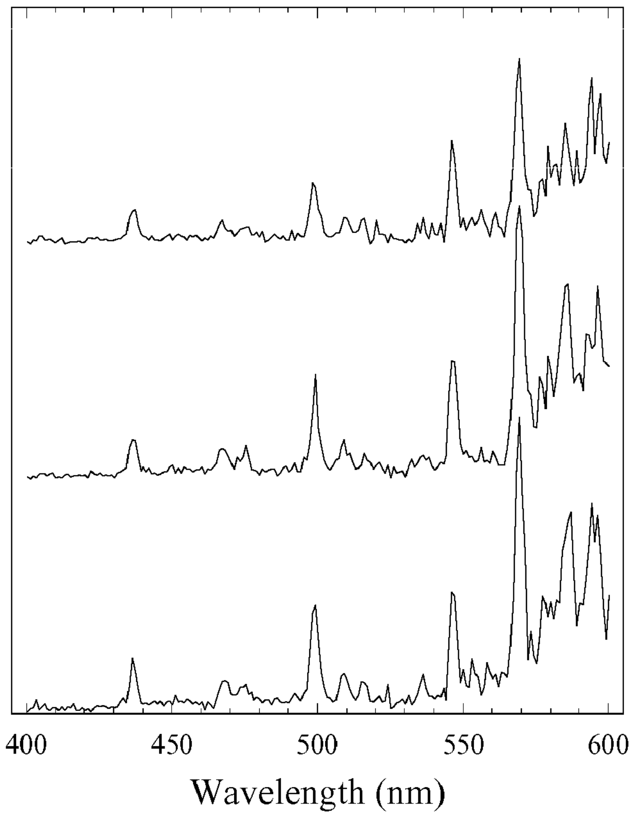


Figure 2 – Three spectra of light pollution reflected from a nearly uniform cloud cover with the telescope aiming above the centre of the city of Guelph. Corrected for spectral response.

completion of the spectrum cannot be taken to be more than an approximation as the conditions for the DDO spectrum are quite different from ours both in apparent dispersion and in visual conditions (a moonlit night). We simply subtracted a constant background, and rescaled the intensity to match the peak at 595 nm. We used a computer-based digitization program performed on the downloaded DDO spectrum. The match of the spectra at 600 nm is not very good and we suspect this principally comes from a broader line width of the DDO spectrum. It is also visually exasperated by the upturn of our own spectrum at 600 nm, which is almost certainly an artifact. (The upturn occurs in a single channel on two of the three cloud spectra. There is no hint of such an upturn on our ground-pointing spectra or on the DDO spectrum.)

Table 1.
Integrated intensities for selected spectral regions. Numbers in parentheses are estimated uncertainties in the last quoted figures.

Spectral range	Relative integral
400–700 nm	1.00 ± 0.15
433–440 nm	0.044(4)
495–502 nm	0.054(5)
543–550 nm	0.047(4)
562–610 nm	0.422(80)

To complete our analysis, we present in Table 1 relative intensities for the brightest segments of the spectrum. The integrated intensity for the entire spectrum is unity. We had to smooth over the gap at 600 nm by removing the upturn and connecting the spectra. Admittedly, there was a significant amount of data manipulation that had to be performed, but in fact the PMT response correction was carefully done and the contribution from the DDO pieced spectrum is only 14% of one of the four quoted integrals. The DDO part of our spectrum contributes more to the overall intensity than to the segment from 562–610 nm, and the correction that we made is such to make our results smaller than they otherwise would be. The numbers are actually quite insensitive to how the connection at 600 nm was performed. The integrals themselves were performed by fitting the spectrum to a cubic spline and using that smoothed curve. In this way we could monitor the smoothness of our digitized DDO spectrum as well as compare numbers done directly from the data. These two different values agreed to well within our quoted uncertainties.

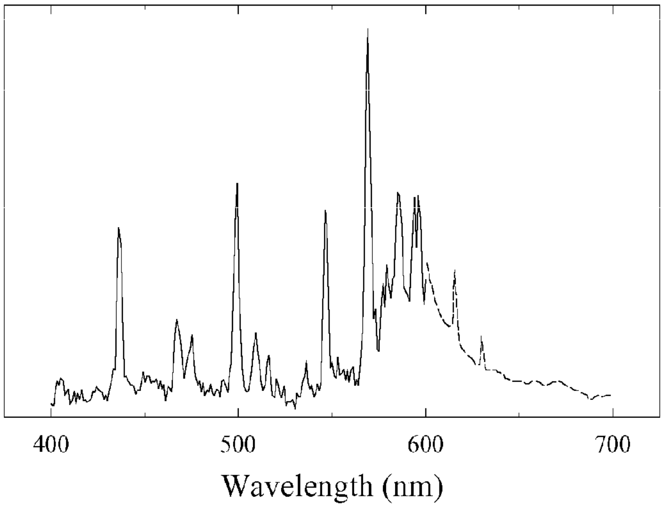


Figure 3 – Sum of the three cloud spectra shown in Figure 2 with an additional correction for Rayleigh scattering. The dashed curve above 600 nm was not acquired in this study (see text).

The data are simply not good enough to warrant line-shape fitting and analysis and so this has not been done. Hence the spectral ranges represent the integration limits without any implication that these represent the line width. In fact, we consider the uncertainties of line widths to be the dominant source of uncertainties in our results.

The broad spectral complex from about 570 nm to 610 nm dominates the spectrum. The dip close to 590 nm is self-absorption, which occurs at the frequencies of the atomic sodium doublet, 589.0 and 589.6 nm. This spectral region accounts for 42% of the total and a filter that worked only there would almost certainly be useful. (Other issues besides removing light pollution are relevant for filter choice. It does one no favours to remove the spectral region of interest for the source being observed.) Three additional "lines" near 438, 500, and 545 nm make up nearly 15% and all of these represent 57% of all of the scattered light pollution over Guelph.

If one were to look for some compromise, say for observing distant galaxies, then removing the lowest of the three "line" features and the broad sodium feature, over the wavelength range given in Table 1, would eliminate nearly 50% of the scattered light pollution while leaving the maximum part of the emission spectra for stars equal to or more massive than our Sun. Specifically, the filter should eliminate the ranges 433–440 nm and 562–610 nm.

4. CONCLUSION AND ACKNOWLEDGMENTS

We have made a measurement of the spectrum of light pollution over Guelph and have tried to be quantitative with respect to the fraction of the integrated pollution that occurs in the strongest of the emission bands. The spectrum so acquired was similar to one taken over Toronto leading to the possibility that the conclusions reached for Guelph might have wider applicability.

We would like to thank B. Morton for technical assistance and Justin Grant for help with our setup. Further thanks are extended to Dr. M. DeRobertis for helpful comments. We acknowledge financial support from the Natural Sciences and Engineering Research Council (NSERC) of Canada.

REFERENCES

Markov, P. 2001, JRASC, 95, 55
Mizon, B. 2002, Light Pollution Responses and Remedies (Spinger-Verlag: London)
Rucinski, S. 2002, `www.ddo.astro.utoronto.ca/ddohome/torontosky.html`
Thessin, R., & Beatty, J.K. 2002, Sky and Telescope, 104, #6, 32

MONIQUE FERGUSON *finished her honours B.Sc. in Physics in 2003 with this light pollution study as her senior undergraduate project. After completing her bachelor of education at Laurentian University, in 2004, she plans to share her love of physics teaching students at the secondary level.*

ROBERT L. BROOKS *is professor of Physics at the University of Guelph. He specializes in experimental atomic, molecular, and optical physics but also teaches astronomy, is the astronomy club coordinator and a member of the RASC. He eagerly awaits the new telescope.*

ENTROPY: A BRIEF REVIEW FROM STEAM ENGINES TO BLACK HOLES

by William W. Dodd, Toronto Centre (William.dodd@utoronto.ca)

"There is no concept in the whole field of physics which is more difficult to understand than is the concept of entropy, nor is there one which is more fundamental."[1]

Introduction

The goal of this article is to discuss entropy in an historical context, and then to present an alternate definition of entropy that is particularly appropriate for astronomical applications, and that is much easier to understand.

Thermodynamics deals with the flow of energy and the conversion of energy within and between systems. There is a basic assumption that, given enough time, an isolated system will always tend towards a state of equilibrium. An isolated system is one that is shut off from the rest of the Universe, no energy enters it and no energy leaves it. What happens inside an isolated system depends only on the particles and energy already inside the system. There are four "laws" of thermodynamics that were first expressed during the 1800s to describe fundamental properties of heat energy.

The zeroth law of thermodynamics states that if two systems are in thermal equilibrium with a third system, then they must be in equilibrium with each other. This concept provides a means for comparing and testing the thermal conditions in a number of systems.

The first law of thermodynamics deals with the quantity of energy in a system. It states that the total energy is always conserved. Whatever energy you gain in one process you lose in another. According to Einstein's famous equation, $E = mc^2$, even mass is just another form of energy. When stars "burn" hydrogen to produce radiation, they do it according to the first law of thermodynamics.

The second law of thermodynamics deals with the quality, or "entropy," of the energy in the Universe. Entropy is defined so that when every aspect of a process is taken into account, the entropy of the Universe never decreases. In *most* physical processes, the entropy of the Universe actually increases; energy is "degraded"; and the Universe cools. In everyday terms, this means that no machine can ever be 100% efficient. In any real process some energy is always "wasted." The word *most* applies to "irreversible" processes. Breaking an egg is an irreversible process and the entropy of the egg system is increased. Theoretically, if a process can be arbitrarily slowed, it can be classed as "reversible." In a reversible process entropy does not change.

The first and second laws of thermodynamics can be illustrated by considering the processes that occur when you turn the lights on, and off again, in a darkened room. When you first switch the lights on, electrical energy flows through the light filaments heating them white hot so that they radiate streams of photons in the visual range. At this stage the room is full of light, and is an open system as energy is being pumped into it. When the switch is turned off, the room approximates an isolated system; no more energy is added or subtracted. After the switch is turned off, the visual photons are quickly absorbed by the walls and an equal amount of energy is re-emitted in the infrared range. While total energy in the room remains constant, the original photons are degraded into more photons each with longer wavelengths. As this happens, the entropy of the light energy systematically increases.

Most events described by quantum mechanics are classed as reversible, and thus they do not change the entropy of the Universe. Rocks and oceans have existed for billions of years. If the entropy of electrons increased every time they orbited about a nucleus, they would soon "crash and burn," atoms would collapse and we would never have come into existence.

The third law of thermodynamics says that the entropy of a system approaches a minimum value as its temperature approaches absolute zero (–273.16° C). Superconductors function in this realm.

Early History of Entropy

In the 1800s steam engines turned heat energy into mechanical energy and powered water pumps in mines, machinery in factories, and engines in locomotives and ships. While engineers and technicians relied on practical experience to make more efficient steam engines, scientists struggled to describe the basic concepts related to energy.

Benjamin Thompson, born in Massachusetts in 1753, was a British loyalist. After the revolutionary war he worked in the British foreign office and held an administrative post in Bavaria. There he was later made Count Rumford. In 1796 he began a systematic study of heat and in 1798 published his results in the *Transactions of the Royal Society of London*. His investigations of the conversion of mechanical energy into heat led him to propose that heat was related to the vibrations of elemental particles, much like sound is related to vibrations in the air. Despite the work of Count Rumford, for another 20 years heat was generally regarded as a caloric fluid that when squeezed out of substances flowed from hot regions to cold regions.

---

[1] Sears, Francis W., *Mechanics, Heat and Sound*, 1958, p 459.

In 1822 the French physicist, Jean Fourrier (the creator of harmonic analysis) developed a rigorous mathematical description of caloric heat flow. In 1824 the French engineer, Sadi Carnot, used the fluid heat model to analyze the workings of cyclic heat engines. He determined that the maximum efficiency, E_{ff}, of a heat engine could be expressed as:

$$E_{ff} = \frac{T_2 - T_1}{T_2},$$

where T_2 is the temperature of the hot region of the engine and T_1 is the temperature of the cold region.

All real engines have some friction and inefficiencies so this maximum is never reached. This rule applied (and still applies) to all heat engines, regardless of the procedures used to convert heat energy into mechanical energy.

In 1848 William Thompson, later Lord Kelvin, defined a temperature scale based on the heat flow in a Carnot engine. This definition of temperature led to the concept of absolute zero (0 K = −273.16° C).

Also during the 1840s an amateur British physicist, James Joule demonstrated that a fixed amount of energy in one form (as contained in a battery, flowing water, a heated reservoir, or compressed gas) could be converted into a fixed amount of another kind of energy such as heat. When all forms of energy were taken into account, no energy was lost or created. In 1847 Hermann von Helmholtz summarized Joule's work and explicitly stated the law of conservation of energy, now known as the first law of thermodynamics. This law of conservation of energy is one of the most fundamental generalizations of science (Asimov 1966).

In 1850 Rudolf Clausius analyzed the maximum efficiency factor of Carnot's heat engines and formulated the second law of thermodynamics: *"it is impossible to transfer heat from a cold to a hot reservoir without at the same time converting a certain amount of work to heat."*[2] The amount of unusable energy at a lower temperature must systematically increase. Various investigators have proposed alternate wordings for the second law to emphasize different aspects, but all versions express the same basic principle. Clausius invented the word "entropy" to describe the unusable energy at a given temperature. Thermodynamic entropy can be calculated by dividing the thermal energy in a system by its temperature.

Since all natural processes, not in the quantum realm, are spontaneous (irreversible), they must lead to increases in entropy. Since the entropy of the Universe increases inexorably, this increase can be used as a measure of time. Sir Arthur Eddington coined the phrase that "entropy is time's arrow."

In chemistry, if the entropy of the compound *AB* is greater than the sum of the entropies of the substances *A* and *B*, then the reaction $A + B \Rightarrow AB$ will proceed because it will lead to an increase in entropy. Thermodynamic entropy can be used to explore the rates and directions of chemical reactions on Earth, in stars, and in interstellar space.

In the 1860s the Scottish physicist, James Clerk Maxwell, and the Austrian physicist, Ludwig Boltzmann, completed a mathematical description of the kinetic theory of gases.

Boltzmann went on to calculate the energy distribution of molecules in an ideal mono-atomic gas using probability distributions. Using probability and statistics to describe an observable property was a major break with traditional physics. His analysis enabled him to predict the average energy per molecule, to derive the universal gas law, and to create an alternate definition of entropy.

Boltzmann defined the entropy, S, as a property of a macroscopic system:

$$S = k \ln W,$$

where k is Boltzmann's constant, and $\ln W$ is the logarithm of the number of possible microstates that corresponds to the observed macrostate of the system. A microstate is a particular arrangement of all the entities in a system.

Phase space is a mathematical creation that includes all possible positions and all possible velocities of the atoms in a system. In a mind experiment, Boltzmann took a volume in phase space and divided it into a set of small cells. Each possible distribution of the atoms among these cells corresponds to a microstate. All arrangements of the atoms are possible, even placing all the atoms in just one cell. It turns out that the greatest number of microstates, and thus the most probable arrangement, corresponds to having an equal number of atoms in each cell. Thus the entropy of a gas is at a maximum when the atoms are uniformly distributed.

Three very important, but subtle, ideas in physics grew from this mind experiment of Boltzmann:

1. In Cartesian phase space the time, distance, and velocity coordinates are continuous so there are an infinite number of possible microstates. Boltzmann could only make the mathematics work if he considered a space that was divided into a finite number of cells. A continuous space that could be infinitely divided was not suitable. Boltzmann's need to apply a limit on the division space may have led to the first glimmerings of quantum mechanics. Planck and Einstein were pioneers in developing the quantum theory. Planck was a student of Boltzmann, and Einstein made extensive use of Boltzmann's work (Tisza 1991).

2. Boltzmann arbitrarily labeled the arrangement with all the atoms in just one cell as "highly ordered" and the arrangement with a uniform distribution as "disordered." Thus, an increase of entropy in the Universe is now associated with an increase in "disorder." In some circumstances, a uniform distribution might be considered as more ordered.

3. Each single microstate is as likely as any other, and a system may rearrange itself from one microstate to another and back again, in a reversible fashion. On a micro scale, activity is reversible and there is no increase of entropy. However, over time it is assumed that a macro system will shift towards its most probable macro state. Over time the entropy of a macro system will increase until a state of equilibrium is reached. Thus, any increase of the total entropy in the Universe is associated with the flow of time.

ENTROPY IN THE 20TH CENTURY

By the early 1900s there were two established views of entropy. From studies of heat flow exemplified by the works of Carnot, Kelvin, and

---

[2] Barrow, Gordon M., *Physical Chemistry,* 6th ed., 1996, p161.

Joule, entropy was regarded as a measure of the quality of the heat energy stored in a system at a given temperature. Based on research exemplified by the work of Boltzmann, Maxwell, Planck, and Einstein the entropy of a system was determined by a statistical analysis of particle motions at the atomic level. In 1922 Leo Szilard developed a rigorous mathematical proof that the statistical approach to entropy contained within it the classical approach to entropy (Rhodes 1986).

In 1948 an American mathematician, Claude Shannon (1948), introduced the concept of information entropy. Shannon's information entropy proved useful in describing the potential quantity of information contained in electronic communications. Information entropy is analogous to thermodynamic entropy, but has no physical relation to it.

A black hole is a super-dense region of space from which no energy can ever escape. It is thought that there is a black hole at the centre of most galaxies, and that stars with more that three solar masses will eventually end up as black holes. By definition, no one will ever see the actual surface of a black hole, but there is a spherical boundary that can be calculated based on the mass of the black hole. This layer is called the event horizon. Once something has crossed the event horizon into a black hole it has vanished from the known Universe for all time. When black holes were studied in the 1960s it was assumed that the entropy of anything falling into a black hole would also disappear from the Universe, in violation of the second law of thermodynamics (Thorne 1994).

Then in 1970 the British cosmologist, Stephen Hawking, discovered a "law of areas" for black holes: the surface area of a black hole's event horizon never decreases. This law was analogous to the second law of thermodynamics: the entropy of an isolated system never decreases. Two years later the American physicist, Jack Bernstein, was able to prove that the area of a black hole's event horizon actually was its entropy. He found that the entropy of a black hole is proportional to the surface area of the event horizon divided by a Planck area (about 10^{-66} cm^2). The entropy of a black hole is very large. If you drop a mass into a black hole, you make the black hole more massive and its event horizon will grow. As a result its entropy will also increase. It is calculated that this increase in the black hole's entropy will more than compensate for the entropy lost by the object you have dropped in. The second law of thermodynamics remains valid for all known systems (Bernstein 2003).

In 1974 Stephen Hawking used this property of black hole entropy to prove that black holes radiate thermal energy. As a black hole radiates; it loses mass; it evaporates. The intensity of Hawking radiation is inversely proportional to the mass of a black hole. A solar-sized black hole radiates at less than 1 K and has an evaporative lifetime greater than 10^{70} years. Most black holes will far outlast any star now shining in the night sky (Hawking 1977).

Some Comments on Open and Isolated Systems

The fundamental assumption of equilibrium is based on the concept of an isolated, or a closed, system. In the laboratory, polished surfaces, insulation, and vacuum chambers are used to approximate an isolated system. Despite these efforts, Sylvan Bloch argues that there is no such thing as a totally isolated system.[3]

> *"A particle in a box is not alone in the universe. It is immersed, in a sea of photons left over from the Big Bang. There is a plethora of stray radiation from natural and human activity on this planet. In our galaxy the largest local source is the Sun, but if we take our box out at night, the moon, planets, stars and other galaxies provide more than enough photons to perturb the oscillator. You can see the stars at night; there are so many photons that many of them will match the energy jump necessary to be absorbed, or they may cause stimulated emission of radiation from an oscillator. You can shield a particle in a box in an electrically conducting box, but there will still be photons associated with blackbody radiation from the inner surface. Make the box superconducting; there will still be photons. Even if absolute zero could be achieved there would still be the zero-point energy and vacuum fluctuations of the electromagnetic field. ... Oscillators will always be perturbed in some way by coupling (photon exchange) with other oscillators in the field."*

Bloch's argument implies that there is actually no such thing as a reversible event, even at the quantum level.

On a much larger scale, galaxies are clearly open systems that convert gravitational potential energy and nuclear potential energy into light energy that is radiated into space. The same description applies to stars.

The Earth is also an open system. The Earth's surface is bathed in radiation from the Sun. This energy drives most of the activity that we observe in the biosphere. If the Earth could be towed into deep space, far away from any star, and left on its own, it would begin to radiate its heat into space. The surface temperature would drop. Water would run down to the oceans and stay there. Biological life would cease. Evolution would cease. The oceans would freeze. The atmosphere would condense. The Earth's heat energy would continue to radiate into space until it became a cold black lump.

A Suggestion to Define Entropy in Astronomical Terms

Over the past two hundred years, investigators have developed at least three approaches to the subject: entropy based on heat, entropy based on probabilities and microstates, and entropy based on information theory.

Entropy is still an active field of investigation and research. The catalogue for the University of Toronto library system lists 193 texts with the word "entropy" in the title. A search of the NASA Astrophysics Data System[4] includes 624 research papers that have been published since 1990 with the word "entropy" in their titles. An Internet search based on "entropy+astronomy" lists over 10,000 sites; "entropy+chemistry" over 29,000 sites; and "entropy+physics" over 49,000 sites. These sites include links to most university departments of astronomy, chemistry, and physics around the world.[5]

In the following paragraphs, an alternate statement of the second law of thermodynamics and a definition of entropy are provided that

---

[3] Bloch, S.C., *Introduction to Classical and Quantum Oscillators,* 1997, p 299.

[4] NASA Astrophysical Data System, `adswww.harvard.edu`

[5] Here are a few representative sites that you might want to review: `www.ncsu.edu/felder-public/kenny/papers/entropy.html; jchemed.chem.wisc.edu/Journal/Issues/1999/Oct/abs1385.html; pespmc1.vub.ac.be/ASC/THERMO_ENTRO.html`

are particularly appropriate for astronomical applications. These forms may be simpler to understand in many applications.

PRELIMINARY IDEAS

The work of researchers like Joule, Boltzmann, Planck, and Einstein has shown that energy can be converted from one form to another. Three simple equations related to photons are of special interest:

$$E = h\nu \tag{1}$$

where E is the energy of a photon, $h = 6.625 \times 10^{-34}$ J·s is Planck's constant, and ν is the frequency of the photon. When the frequency of a photon is large, its energy is relatively large:

$$c = \nu\lambda \tag{2}$$

where $c = 2.998 \times 10^{10}$ cm s^{-1} is the speed of light, ν is the frequency of a photon, and λ is the wavelength of the photon. With this equation, any discussion involving frequencies of photons can be easily converted to a discussion involving wavelengths. Combining (1) and (2) the total energy, E, associated with a group of n photons with average wavelength λ can be expressed as:

$$E = \frac{nhc}{\lambda}. \tag{3}$$

Most of our information about the Universe involves photons. In the standard Big Bang model, at the beginning of the Universe, there are about a billion photons for every proton and every neutron (Sciama 1971). As the Universe expands, all of these photons are stretched to longer wavelengths and lower energy. This stretching is measured in the cosmic redshift of the light from distant galaxies. The entropy of everyday events is *"swamped by the immense quantity of entropy that resides in the microwave background [radiation]."*[6] In addition, the dominant activity in every star and every galaxy involves the conversion of mass-energy into photon-energy via nuclear reactions, which systematically increase the entropy of the Universe.

We literally see the results of increasing entropy and the conversion of high-energy photons to lower-energy photons every day. Our Sun is powered by nuclear reactions in its core where the temperature is approximately 15,000,000 K. These reactions produce vast amounts of gamma rays and X-rays (high-energy photons). Then it takes about 100,000 years for these photons to work their way to the surface of the Sun. As the photons move outward they interact with the atoms of the solar mass. These interactions include collisions, and absorption and re-emission. In these interactions the original high-energy photons are reduced to many more photons, each with a longer wavelength and a lower energy. At its surface the Sun has the appearance of a giant ball burning at only 6300 K (Menzel 1959). Some of this light reaches the Earth's surface and illuminates our world. Without the second law of thermodynamics, and the resultant increase of entropy, the Earth would be swept by high energy X-rays and gamma rays instead of gentle sunlight. We would be toast. As you gaze out the window, you are observing the results of solar-scale entropy at work. When you gaze at stars through your telescope, you are observing entropy at work on a cosmic scale.

ASTRONOMICAL ENTROPY

In a Universe filled with photons, and in which the primary activity of stars and galaxies involves producing still more photons, it is reasonable to define entropy and the second law of thermodynamics in terms of photons.

An alternate form for the second law of thermodynamics:
For all the photons involved in a real process, the average wavelength is increased.

An alternate definition of entropy:
The entropy of a system is characterized by the average wavelength of all the photons in the system.

Including the word "average" in these statements indicates that a statistical approach is required. In any irreversible process, the number of higher-energy photons is decreased and the number of lower-energy photons is increased. In a closed system, the increase in the number of low-energy photons would have to be just sufficient to keep the total energy in the system constant. It is more difficult to extract work from a system with lower-energy photons than it is from a system with higher-energy photons. The rate of increase of the average photon wavelength in a system could be interpreted as a measure of the passage of time. As the temperature of a system approached absolute zero, the average photon wavelength would approach infinity. In systems involving other than photon energy, it is possible to convert other types and quantities of energy into the numerical equivalent of photons, with a suitable range of wavelengths.

The following simple example illustrates how the astronomical version of the second law might be used. Consider the energy in an isolated system that initially contains 5000 photons with an average wavelength of 1.0 cm. Suppose that after some real process the system is found to contain 10,000 photons with an average wavelength of 2.0 cm.

Initial Energy:

$$E = \frac{nhc}{\lambda} = \frac{5000 \times 6.625 \times 10^{-34} \times 2.998 \times 10^{10}}{1.0} = 9.93 \times 10^{-20}\ \mathrm{J}$$

Final Energy:

$$E = \frac{nhc}{\lambda} = \frac{10000 \times 6.625 \times 10^{-34} \times 2.998 \times 10^{10}}{2.0} = 9.93 \times 10^{-20}\ \mathrm{J}$$

The total energy in the initial and final states remains constant (first law), however the average wavelength has increased (second law). An average photon in the initial state has twice the energy of an average photon in the final state. The final state is not necessarily more disordered, but its photons have less potential for producing work via conversion into alternate types of energy.

---

[6] Peacock, John A., *Cosmological Physics,* 1999, p 277.

SOME SPECULATION

"irreversible processes can occur that create entropy and...this entropy can be in the form of photons; photon number is not preserved."[7]

Expressing the second law of thermodynamics in terms of photons leads to the implication that photons experience some form of "cosmic pressure" to evolve towards lower energies and longer wavelengths. The tendency for photons to evolve towards longer wavelengths could be the ultimate source of all evolution in the Universe.

To this point, no mention has been made of the role of neutrinos in the evolution of entropy. The number of primal neutrinos, created in the early stages of the Big Bang, is thought to be about three quarters of the number of primal photons (Peebles 1993). This would still correspond to about a billion neutrinos for every neutron and every proton in the Universe. The Universe is swimming in neutrinos, however, particle physicists have found evidence that a conservation law applies to neutrinos, so the total number of neutrinos should remain constant in any process. If the number of neutrinos in the Universe remains constant, they can have only a minor role in the growth of entropy in the Universe.

SUMMARY

Entropy and the second law of thermodynamics have been topics for research during the past two centuries. The nature of heat and the design of heat engines spurred the earliest investigations. Research into the behaviour of gasses led to a statistical approach to entropy. Later work in information theory, and investigations of the properties of black holes created a renewed interest in the concept of entropy.

An alternate version of the second law of thermodynamics has been presented. This form was chosen because it is relatively simple and because it is appropriate for describing activity in a Universe dominated by the evolution of photons.

REFERENCES

Asimov, I. 1966, The History of Physics (Walker and Co.: New York)
Bernstein, J. 2003, Scientific American, August
Hawking, S. 1977, Scientific American, January
Menzel, D. 1959, Our Sun (Harvard University Press: Cambridge)
Peebles, P.J.E. 1993, Principles of Physical Cosmology (Princeton University Press: Princeton)
Rhodes, R. 1986, The Making of the Atomic Bomb (Simon & Schuster: New York), 19
Sciama, D.W. 1971, Modern Cosmology (Cambridge University Press: Cambridge)
Shannon, C.E. 1948, Bell System Tech. J., 27, 329-423, 623-656
Thorne, K.S. 1994, Black Holes & Time Warps (W.W. Norton & Co.)
Tisza, L. 1991, in Thermodynamics: History and Philosophy, ed. Martinas, Ropolyi, & Szegedi

William Dodd has a particular interest in the educational and historical aspects of astronomy.

---

[7] Sciama, D.W., *Modern Cosmology,* 1971, p 173.

Transit Turns

by Bruce McCurdy, Edmonton Centre (bmccurdy@telusplanet.net)

> *"I had a feeling once about Mathematics - that I saw it all. Depth beyond depth was revealed to me - the Byss and Abyss. I saw - as one might see the transit of Venus - a quantity passing through infinity and changing its sign from plus to minus. I saw exactly why it happened and why the tergiversation was inevitable - but it was after dinner and I let it go."*
>
> – Sir Winston Churchill

"Be careful for what you wish!" my grammatically-correct mother reminds me occasionally, as mothers are wont to do. As I closed out my June column, which I thought was my last word on transits of Venus, I idly speculated about needing 100,000 years of data to see their long-term structure.

Well, guess what? In pursuing another matter entirely - occultations of Saturn by Jupiter, but that's a story for another time - I was referred to the Web site of one Aldo Vitagliano. A professor of general and inorganic chemistry at the University of Naples, Italy, Vitagliano has an amateur interest in celestial mechanics, and has developed *Solex 8.5,* a "free computer program modeling N-body dynamics of the solar system" using numerical integration. *Solex* has a high degree of accuracy, and gained some notoriety by performing the widely-accepted calculation that the last time Mars was closer to Earth than in 2003 was on September 12, -57,617 (Sinnott 2003).

Vitagliano has also applied his formidable program to the matter of Venus transits. His Web site included a list of all such events from 100,000 BC to AD 100,000 (`main.chemistry.unina.it/~alvitagl/solex/Ventrans.txt`). I had wished for 100,000 years of data, and now I had double that! 42 printed pages of data, one line to a transit. Embedded therein must lie the proof (or otherwise) to my previous suppositions, plus the promise of further surprises. How is an ornery old orbital oddball supposed to resist?

The first task was the simple matter of laying out data in a panorama. Fortunately, I already had a methodology and a knack for pattern recognition that allowed me to exercise some shortcuts, and I was extremely fortunate that the resultant output reconciled to Vitagliano's total of 2544 transits on the first attempt. The still unwieldy result was a spreadsheet some 823 lines long, with each line representing 243 years and 2, 3, or 4 transits. For the entire period without exception, transits occur at either node in singles or pairs, with no gaps and no trios, for an average of 1.55 transits per window. The panorama is relatively narrow, with only 9 columns at the descending node and 10 at the ascending, incorporating every last event. Selected portions have been condensed into the accompanying tables.

My labours bore immediate fruit: unambiguous confirmation of my conclusion that transit series wind back and forth over extended periods. In his wonderful pamphlet *Transits,* Meeus (1989) asserts, specifically with respect to Mercury, that "Series start and die." And indeed that is the norm with all sorts of periodic phenomena, even ones as long-lasting as the famous Saros cycle of eclipses; they display a long-term evolution with series starting at one pole, gradually maxing out at the optimum central event, before receding to the opposite pole. Related series follow, always migrating in the same direction. But the pattern of Venus transits is unusual in that series do not die, they *hibernate* for long periods before reawakening. They can migrate in either direction, in effect changing their sign.

I have numbered the columns containing the earliest events A1 and D1 respectively, with subsequent series at 8-year intervals. Conveniently, series of the same number are separated by the semi-period of 121.5 years (*e.g.* A8 = 1882; D8 = 2004). Currently, series A7, A8, D8, and D9 are active.

The descending node series D8 is also active at both extreme ends of the data set. The transit of -99,813 is a member of D8, and there are 25 more through -93,738. Then there is a lengthy gap as the descending node transits, always in singles or pairs, oscillate from series D7 through D1 and back, all transits occurring 8 years "too early" to belong to series D8. But D8 is reactivated in -26,427 through -22,296 (18 transits), then again from -3099 through 3705 (29 transits), then 9537 through 14,889 (23 transits). Finally after another long gap there is an unbroken sequence of 84 transits from 79,766 through 99,935 and presumably beyond.

Table 1 shows the migration of series at the descending node from -100,000 to +20,000. The series appear to vibrate like a string around the mean, effectively neutralizing the top-to-bottom slope. As I interpret it, these twists and turns over the extremely long term establish a near-resonance, at least with respect to the nodes, of 395 rotations of Venus to 243 of Earth. The oscillations would be due to factors such as the changing orientation of the lines of apsides to the line of nodes, and the varying eccentricities of Venus and Earth.

The most asymmetrical sequences in the entire 200,000 years occur right at the beginning; starting in -99,975 the intervals are 161.5 - 8 - 73.5 years.

Transits are not evenly distributed throughout the period under study. Per 10,000 year interval (each of which includes approximately 41 periods of 243 years):

-100,000	to	-90000	111
-90,000	to	-80,000	124
-80,000	to	-70,000	101
-70,000	to	-60,000	108
-60,000	to	-50,000	116
-50,000	to	-40,000	131
-40,000	to	-30,000	135
-30,000	to	-20,000	139
-20,000	to	-10,000	128
-10,000	to	0	122
0	to	10,000	115
10,000	to	20,000	118
20,000	to	30,000	123
30,000	to	40,000	127
40,000	to	50,000	130
50,000	to	60,000	133
60,000	to	70,000	154
70,000	to	80,000	155
80,000	to	90,000	132
90,000	to	100,000	142

There is therefore a range from ~1.2 transits per window at a given node around -75,000, to ~1.9 transits around +70,000. Obviously there are many more single transits in the first instance, many more pairs in the latter. Surely this must be a result of the changing inclination of the orbital plane of Venus, with shallower values of *i* more conducive to multiple events. Indeed, Meeus (2002) shows Venus maintaining a relatively high inclination of > 3° throughout the 200,000-year period, varying in a curve almost inversely proportionate to this distribution. In a subsequent correspondence, Meeus (2004) provided the following extreme values, where t is the time in thousands of years from AD 1850:

t	inclin.(deg)
-132	3.1183
-77	3.9846
-22	3.2294
+22	3.5279
+72	3.1671
+119	3.5643

This places the maximum and minimum values of *i* very close to -75,000 and +75,000 respectively, in very good agreement with the distribution above.

Presumably if the inclination of Venus were a little lower, say closer to 2°, it would be possible for transits to occur in sets of three or even more at eight-year intervals at the same node. Meeus' figure indicated values of *i* closer to 1° half a million years hence. Meeus himself stressed that the aim of the theory he used to obtain these values, that of Bretagnon (1974), "was to give a good idea of the past and future evolution of the planetary orbits, not to provide *very* accurate data." In other words, the curve should be the right shape, but the values increasingly unreliable.

So I posed the question to the man whose number crunching *Solex 8.5* had already done calculations eons into the past and future. Vitagliano (2004) graciously replied that there will most likely be a triple transit in 166,009, -166,017, -166,025, and more certainly in 170,634, -170,642, -170,650, and 170,877, -170,885, -170,893. The three events listed above are almost a classic case of changing conditions near a threshold. The first is a single, almost fluke occurrence where there are two events near the extreme values bracketing a third, almost exactly central event. At this point the possible range of events has crossed the boundary from $(1 < n < 2)$ to $(2 < n < 3)$, but remains much closer to 2 than 3. Circumstances have to be just right for a triplet; the two planets have to be in the right place at exactly the right time.

The second and third triples listed above occur a few millennia later when the inclination is a little more comfortably within the range required, and the middle event does not have to be so exactly central. Transits would still occur most commonly in pairs, with the occasional exceptional trio. Presumably there would no longer be single transits at that node. Note that the two triples are related to each other as they are separated by the established interval of 243 years. These triples are members of the descending node series I have numbered D5-D6-D7 (in the first instance) and D4-D5-D6 (in the other two). The shift of one series is to be expected after an interval of a few millennia, and is consistent with my large panorama.

Vitagliano also explored the far future when the value of *i* will reach an extreme minimum of 0.56° around the 557th millennium. In a test century starting in 550,001, *Solex* found no fewer than a dozen transits, including eight in a row at eight-year intervals at the ascending node. It seems logical that the lower inclination (only a sixth of present value) leads to the consecutive chords of Venus' passage over the Sun being much closer together, presumably at an average separation of ~4 arcminutes as opposed to the current 20-24. Because of this, events could take place at a much greater longitudinal displacement from the nodes; ergo more series are simultaneously activated.

This leaves one to wonder if one's distant descendants will consider transits of Venus to be commonplace, unremarkable events. I certainly hope not. Having gone to considerable lengths to glimpse the "black planet" completing the Transit of 2004 within 2° of the horizon, I remain awestruck at the precise clockwork of the cosmos. That humankind is able to so accurately predict such events, yet remains utterly powerless to affect them, provides further proof that our capabilities, while impressive, are not limitless.

References

Bretagnon, P. 1974, A&A, 30, 141
Meeus, J. 1989, Transits, (Willmann-Bell,

Inc.: Richmond), 7
Meeus, J. 2002, More Mathematical Astronomy Morsels, (Willmann-Bell Inc.: Richmond), 208
Meeus, J. 2004, private communication
Sinnott, R. 2003, Sky & Telescope, 105, 6, 94
Vitagliano, A., `main.chemistry.unina.it/~alvitagl/solex/Ventrans.txt`
Vitagliano, A. 2004, private communication

Table 1

D1	D2	D3	D4	D5	D6	D7	D8	D9	Reps
							-99813	-99805	11
							-97140		11
						-94475	-94467		4
						-93503			8
					-91567	-91559			2
					-91081				8
				-89145	-89137				2
				-88659					8
			-86723	-86715					2
			-86237						8
		-84301	-84293						4
		-83329							10
	-80907	-80899							8
	-78963								34
	-70701	-70693							16
		-66805							44
	-56121	-56113							7
	-54420								22
-49082	-49074								19
	-44457								10
	-42027	-42019							9
		-39832							4
		-38860	-38852						8
			-36908						3
			-36179	-36171					8
				-34227					2
				-33741	-33733				8
					-31789				3
					-31060	-31052			11
						-28379			8
						-26435	-26427		18
						-22061			16
					-18181	-18173			10
					-15751				36
					-7003	-6995			11
						-4322			5
						-3107	-3099		10
							-669		5
							546	554	14
								3956	23
							9537	9545	10
							11967		8
						13903	13911		5
						15118			8
					17054	17062			5
					18269				7
				19962	19970				7

Table 1. Compressed panorama of transits at the descending node, -100,000 to +20,000, displays the "on again, off again" nature of transit series. Each row represents the first member of a group of transits of similar sequence, with the number of repetitions in the right hand column. For example, the years 546 and 554 are the first of a group of 14 pairs involving Series D8 and D9, including the current pair of 2004 and 2012 and ending in 3705 and 3713. By 3948 Series D8 has "turned off" as Venus passes just south of the Sun, so a sequence of 23 periods of single transits of Series D9 commences in 3956. Series D8 then resumes in 9537.

The chord inscribed by Venus across the Sun migrates from one series member to the next. The direction of this displacement can be discerned from the slant of the table. Left is north, right south. In the present day, the left-to-right slope means the chord is migrating southward. At the turning points where the migration of the chord reverses direction, a series begins and ends at the same pole - like an occultation series of, say, Aldebaran - and the panorama itself reverses its field. This always happens at the extreme Series D1 and D9, but there are occasional kinks elsewhere in the curve, due to the complex interrelationship of several variables in the two orbits. The ascending node panorama is similar in appearance, but the polarity is reversed.

The Reps column reveals the relative frequency of **pairs** of transits to *singles,* which varies roughly with the inclination of Venus. Singles are much more common towards the top of the table.

Table 2

A3	A4	A5	A6	D1	D2	D3	D4	D5	D6	D7	D8	Reps
50687					50800	50808						7
52388	52396				52501	52509						1
52631	52639				52744							14
56033	56041			56138	56146							2
	56527			56624	56632							10
	58957	58965		59054	59062							13
	62116	62124			62221							7
	63817	63825			63922	63930						13
	66976	66984				67090						3
	67705	67713				67819	67827					10
	70135	70143					70257					1
	70378	70386					70500	70508				10
	72808	72816						72938				2
	73294	73302						73424	73432			9
	75481	75489							75619			2
	75967	75975							76105	76113		11
	78640	78648								78786		4
	79612	79620								79758	79766	10
		82050								82188	82196	5
		83265	83273							83403	83411	3
		83994	84002								84140	10
			86432								86570	3

Table 2. Even a condensed distribution table of the entire period under study is much too lengthy to reproduce here, as a new line is generated by a change at either node. (If interested, email the author for an *Excel* file.) The overall effect is two meandering curves, out of phase with each other, somewhat reminiscent of a double helix. The 36,000-year portion represented here includes a most peculiar period from AD ~59,000 to 82,000, when there is exceptional stability at the ascending node with an unbroken sequence of 95 consecutive pairs of transits at A4 and A5. Meanwhile, at the descending node, transits gradually migrate from Series D1 all the way to D8. The sequence of transits goes from 8 - 89.5 - 8 - 137.5 around 59,000, to a symmetrical 8 - 113.5 - 8 - 113.5 around 71,000, to 8 - 137.5 - 8 - 89.5 around 80,000. This oscillation will all take place at one node! I have no mechanism in mind that could explain this; however the imbalance during this period would appear to be responsible for the differing distribution curves in Figure 1.

Bruce McCurdy is active in astronomy education with the RASC Edmonton Centre, Odyssium, and Sky Scan Science Awareness Project. He currently serves National Council as Astronomy Day Coordinator. Bruce often contemplates the mathematical mysteries of the cosmos during his daily transit with his dog, Venus.

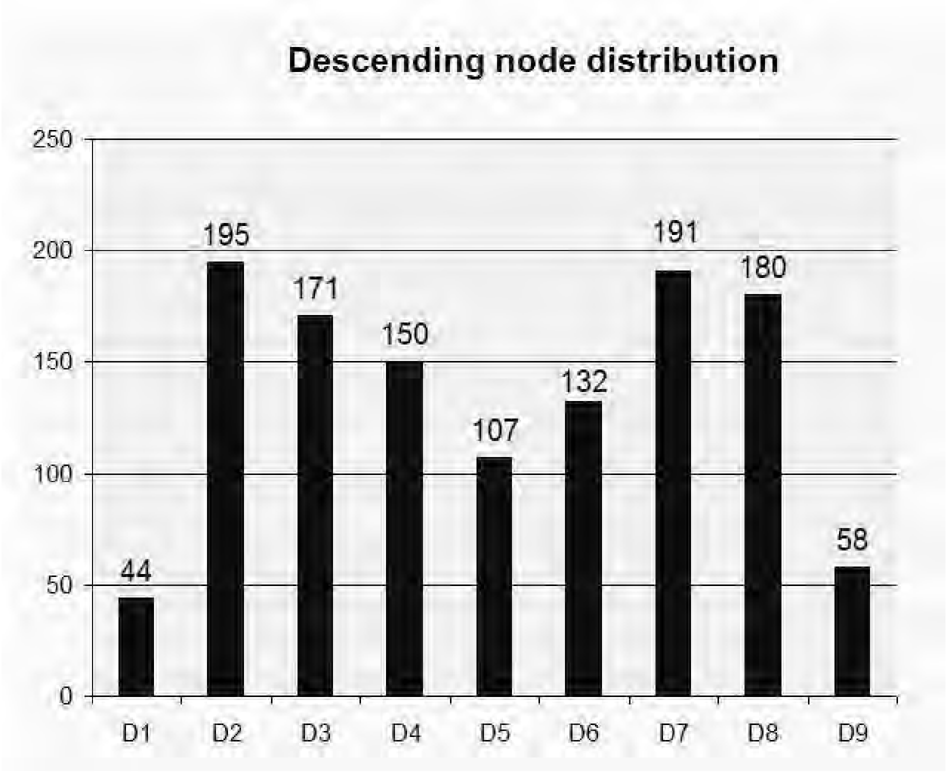


Figure 1 – Over the 200,000 years, there are 1316 transits at the ascending node involving 10 different series, and 1228 at the descending node (9 series). There is a very peculiar, asymmetric distribution: the ascending node series have a single peak (standard Bell curve), whereas that of the descending node displays a more regular sinusoidal curve with a double peak. One possible explanation is that the period under review is still not long enough for the law of averages to iron out such wrinkles; to oversimplify, there are two full oscillations at the descending node and only 1.5 at the ascending during this time.

Figure 1

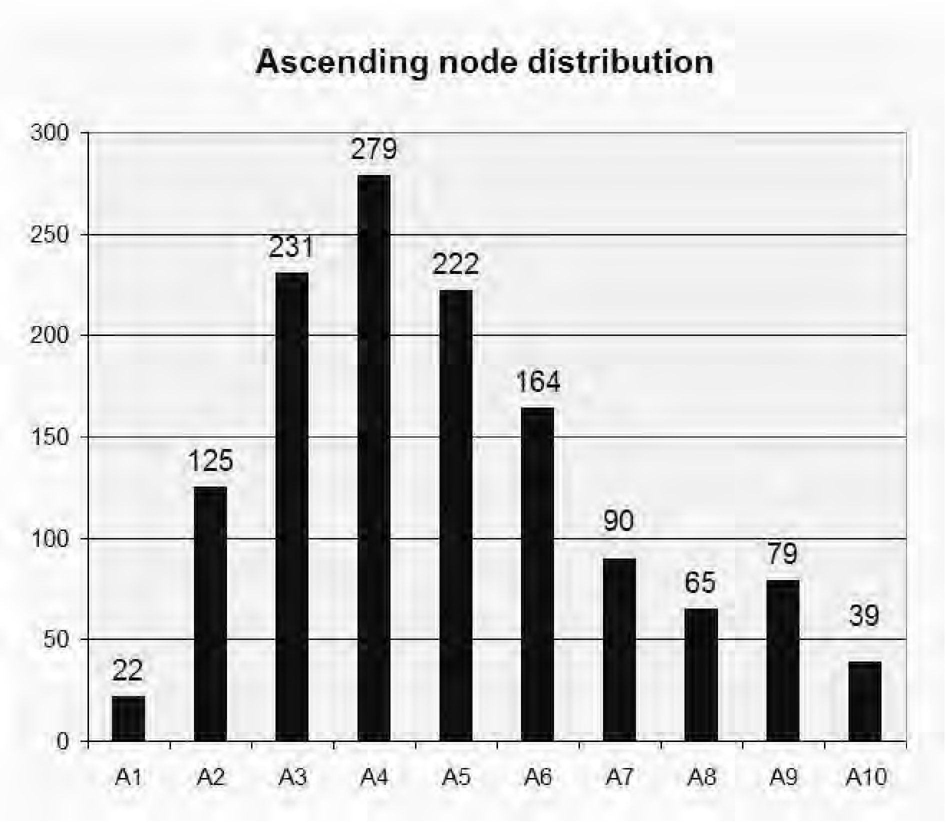


Figure 2 – The long-period evolution of the inclination of Venus displays a super-period of some 1.1 million years. Throughout the present era Venus is near its maximum value, and remains above 3° for several hundred thousand years. This forces the current arrangement of transits always occurring in singles or pairs. Half a million years hence, when the value of *i* recedes below 1 degree, transits will become much more commonplace. Figure graciously provided by Aldo Vitagliano was originally published in the Italian popular astronomy magazine Coelum.

Figure 2

A Moment With…

Dr. Philip Stooke

by Philip Mozel (philip.mozel@osc.on.ca)

Q: What do you get if you combine a geographer with an astronomer? A: Dr. Philip Stooke of the University of Western Ontario. This fusion came about due to his interests in geology and space dating from the *Apollo* voyages to the Moon. Throw an interest in maps into the mix and you have a planetary geologist and cartographer.

Charting distant planets, as difficult as it might be, is still an exercise in creating maps of essentially spherical objects. Dr. Stooke developed a new method of map projection that could be applied to non-spherical objects, *i.e.* asteroids and small moons. This led to the publication of an on-line atlas of the small bodies of the solar system.

A work currently in progress is an atlas of lunar exploration. It will not be your typical atlas but will instead trace in detail some of the lesser known and behind-the-scenes activities during our discoveries on the Moon. For example, anyone remotely interested in the subject knows where *Apollo 11* landed, *i.e.* the Sea of Tranquillity. But how was the exact spot chosen? The atlas will publish, for the first time, the minutes of the site-selection meetings.

Before *Apollo,* came *Ranger, Surveyor,* and *Lunar Orbiter,* and the atlas will examine these missions and Russian probes closely. As part of these analyses, the locations of the various spacecraft will be pinpointed as accurately as possible. Remarkably, the precise locations of the landing sites of some lunar probes are not known. For example, one of the *Lunakhod* rovers was parked (or broke down) in such a position that its retro-reflectors no longer return pulses of laser light to Earth. Using photographs returned by *Lunakhod, Apollo 15,* and *Clementine,* Dr. Stooke has proposed a location for the landing site some five kilometres from the one usually accepted. This information has been passed to the Jet Propulsion Laboratory, which will attempt a laser detection of the vehicle on the Moon's surface.

Spacecraft have also gone "missing" on Mars. For example, the precise location of the *Viking 2* lander is not known with certainty. *Viking* orbiter images are not of sufficient quality to unambiguously determine the site but one bright pixel may represent the spacecraft. Dr. Stooke is using *Mars Global Surveyor* photographs in a confirmatory role and that one pixel does look promising. Finding the lander will help determine what kind of surface it is sitting on. A comparison can then be made with the appearance of this material from orbit and the landing site put into a regional context and compared with other sites. Eventually, an atlas of Martian exploration will be prepared.

Dr. Stooke's interest in cartography is not restricted to cutting-edge mapping of worlds far distant in space. He has also studied maps far removed from us in time. It struck him as odd that the oldest known map of the Moon was one ascribed to Leonardo da Vinci. Surely, given humanity's interest in the Moon, someone much earlier had prepared a chart that has gone unrecognized. A search through many images from the fields of art and archaeology revealed a possible candidate fully ten times the age of da Vinci's map. This time the canvas is stone.


Dr. Philip Stooke

Europe and the British Isles are dotted with megalithic monuments, the most famous being Stonehenge. There are others such as Newgrange, in Ireland and, not far from it, Knowth. Knowth is a passage tomb, some eighty-four metres in diameter, constructed of a ring of giant boulders and roofed over, essentially forming an artificial hill. Passages, opening from the east and west sides, lead to the interior. Engravings of hundreds of spirals, arcs, and circles decorate the stones. On the end wall of the east passage are the engravings that Dr. Stooke interprets as five thousand-year-old maps of the Moon.

The putative maps are essentially groups of roughly concentric arcs which, he suggests, represent the lunar maria. As Moon watchers know, the orientation of the maria changes as, first the Moon rises and the eastern limb is uppermost. On the meridian, the northern limb is at the top. As the Moon sets, the western limb is uppermost. These changing orientations seem to be reflected in the way a series of arcs have been carved at Knowth. Furthermore, at certain times of the year the rising Sun and Moon shine down the eastern passage and illuminate the carvings.

Stonehenge has come under scrutiny as well. The tall trilithons of that monument are also arranged in an arc and have been called a "map of the Moon on legs" by Dr. Stooke.

Such interpretations are certainly controversial. But whether mapping objects of a celestial nature here, or in space, Dr. Stooke is providing us with new ways of looking at the universe.

REFERENCES

Stooke, P.J. 1994, Journal for the History of Astronomy, 25, 39
Stooke, P.J., Stooke Small Bodies Maps, `www.psi.edu/pds/archive/astdata03/maps/`
Stooke, P.J., Cartography of Non-spherical Worlds, `publish.uwo.ca/~pjstooke/plancart.htm`
Stooke, P.J., The Lunar Maps of Knowth, `publish.uwo.ca/~pjstooke/knowth.htm`

Philip Mozel is a past National Librarian of the Society and was the Producer/Education at the McLaughlin Planetarium. He is currently an Educator at the Ontario Science Centre.

The Earth Centered Universe™
Planetarium and Telescope Control Software

New V4.0 Released!

The Earth Centered Universe Pro (ECU) has been the Canadian choice of amateur astronomers for over a decade. This practical tool for astronomy enthusiasts — known for its ease of use, reasonable price, rich feature set, and lightning fast speed — has been upgraded yet again. See our web site for a complete list of features and to take advantage of the free demo version.

Just a few of the features:

- Includes the Sun, Moon, Planets, and over 200,000 asteroids and comets. **Easily download new comets and asteroids from the Internet** from within ECU! Includes powerful animation features.
- Stellar databases include the Yale Catalog (9100+ stars), SAO Catalog (245,000+ stars), Tycho-2/Hipparcos Catalog (2,400,000+ stars), and the **Hubble Guide Star Catalog** (15,000,000+ stars). Also reads the amazing **US Naval Observatory S-2.0** Catalog which contains 525,000,000+ stars to fainter than 19th magnitude!
- The huge deep sky databases include the respected 10,500+ object Saguaro Astronomy Club database and the 73,000+ galaxy strong **PGC Catalog**.
- Other databases include the **General Catalog of Variable Stars** and the **Washington Visual Double Star Catalog**. Add your own objects, too!
- **Prints highly-configurable, high-quality star charts**. Now includes a new split-chart feature and charts can be printed in full colour.
- Powerful interface to most computerized telescopes including the Meade **LX200** and **Autostar series**, the Celestron **NexStar**, most Digital Setting Circles, and many more. Many more telescopes are supported through complete support of the **ASCOM** initiative.
- Includes an image viewer and hundreds of astronomical images.
- **Price: CDN$79.95**+$4.50P&H+GST/HST (see web site or call for upgrade prices)

Customers have had this to say:

"Thanks again for a GREAT piece of software for the backyard guy. Having tried several, I keep coming back to ECU for the best all-around package for my use."
- Woody S., South Carolina

"I received the new release of ECU (V4.0) and loaded it on my telescope computer. The new features are very nice additions to the most efficient planetarium program with telescope control on this planet"
- Richard M., New York

NOVA Astronomics

website: www.nova-astro.com e-mail: info@nova-astro.com phone: (902) 499-6196

The Skies Over Canada

Observing Committee News

by Christopher Fleming (observing@rasc.ca)

Following the National Council meeting in October 2002 Stan Runge of the Winnipeg Centre approached the committee about creating some new, detailed observing forms that would be specific to the Society's Messier and Finest NGC Certificate programs. At that time he handed me some prototypes he had made; I thought they were very good and that the committee could use them as the basis from which the project may evolve. A few months later I was discussing the idea with London Centre member Dan Williams and he offered to help develop the overall design of the forms that would incorporate all of the concepts that were proposed. Initially the prototypes had two objects per page and were printed on upright, letter-sized sheets of paper.

In order to add more content and to provide a larger area to make a drawing, Dan suggested that we change to a landscape view format and insert just one object per page. This idea worked out very well and we were able to incorporate a lot of detail while leaving plenty of room for notes and drawings. The detail includes all of the known parameters about each object such as its name, designation, type, location, magnitude, size, and distance. Also included are handy references to chart numbers in *Sky Atlas 2000* and *Uranometria 2000* for each object listed. In addition, fields for writing down the date, time, telescope, eyepiece, magnification, and observing location are included as well as direction indicators around the drawing circle.

The intent of this project is to make life easier for observers by saving them the time it takes to look up all of the known parameters about each object. With this approach all they have to do is write down a few local details and a description of the object. To get the maximum benefit from these forms, observers will be encouraged to make a drawing, since that is the best way to discover fine, subtle details within astronomical objects. Many observers, including myself, are surprised to learn that their artistic skills are better than they thought, and with a little practice you will become a better observer for it. By the time this article reaches you the forms will be available on the RASC Web site in Adobe Portable Document File (pdf) format. Each file for the Messier and Finest NGC lists will be about 1 megabyte or so in size.

The Messier program log forms can be found at: `www.rasc.ca/observing/page3.html`.

The Finest NGC program log forms can be found at: `www.rasc.ca/observing/page4.html`. We welcome comments and suggestions about the forms.

Since the last report there has been one Explore the Universe Certificate awarded, as well as 3 Messier Certificates and 4 Finest NGC Certificates.

The Explore the Universe Certificate Recipient is:

Name	Centre	Date Awarded
Kevin Gallant	Regina, Sask.	May 2004

The Messier Certificate Recipients are:

Name	Centre	Date Awarded
Ted Dunphy	Moncton, N.B.	April 2004
Marie Fisher	Sarnia, Ont.	May 2004
Norm Willey	Victoria, B.C.	May 2004

The Finest NGC Certificate Recipients are:

Name	Centre	Date Awarded
John Appleyard	London, Ont.	May 2004
Robert Chapman	Toronto, Ont.	May 2004
Sam Ferris	Regina, Sask.	May 2004
Robert Brann	Regina, Sask.	May 2004

Congratulations to all!!

The new observing sections that the committee has developed over the last few years continue to be updated on a regular basis with new content; the following highlights some of their features. The Asteroids Section has sample charts for the brightest asteroids currently visible, which you can print for use in the field. These charts feature the track of asteroids tenth magnitude or brighter and visible during the nighttime on the dates indicated, sometime between dusk and dawn. Specific locations for the asteroids are plotted on the charts at three-day intervals over periods ranging from several days to two weeks or more.

The bright asteroid Vesta, 530 kilometres in diameter, will be an excellent target for asteroid observers this year, and it will be visible from June through December. Vesta will be brightest in early September, when it will reach 6.1 magnitude; a chart will be available for download and/or printing on the Sample Charts page that is part of the Asteroids Section. You can find the Asteroids Section at: `www.rasc.ca/observing/asteroids`.

The Special Projects Section has information about three major astronomical events up to June 2004, which included the Perihelion Opposition of Mars during the summer of 2003, the Total Lunar Eclipse of November 8, 2003, and the rare Transit of Venus on June 8, 2004. We will continue to provide these special information pages for upcoming notable astronomical events and we invite those who might like to create a special project page for their particular observing interest to contact us. We extend our sincere thanks to Geoff Gaherty, who provided the content for the Mars Opposition and Lunar Eclipse pages.

The variable-star observing community has warmly received the recent addition of the Variable Star Section in the spring of 2004. It contains all the information a new variable-star observer will need to get started in this interesting and important work. I highlight one of the most famous variable stars since it is currently visible and an excellent target for a new variable-star observer. Omicron Ceti, proper name Mira, is a Long Period Variable (LPV) that is the prototype of its class and at maximum is the brightest of the LPVs. Ancient astronomers gave it the title "Mira the Wonderful" in regards to its pattern of completely disappearing and then reappearing as one of the most brilliant stars in its part of the sky. Charts for Mira can be found on the Sample Charts One page of the RASC Variable Star Section.

Christopher Fleming is Chair of the RASC Observing Committee and Observers' Chair in the London Centre. He enjoys all types of observing, especially Deep-Sky, Lunar, Double Stars, and Variable Stars. Chris is also a musician and Webmaster of the London Jazz Society's Web site.

Astrocryptic

by Curt Nason, Moncton Centre

The solution to last issue's puzzle:

1 T	I	2 R	I	3 O	N	■	4 C	5 I	R	6 C	L	7 E
H	■	E	■	R	■	8 O	■	N	■	H	■	L
9 U	R	A	N	I	U	M	■	10 D	R	A	C	O
N	■	L	■	O	■	I	■	I	■	R	■	G
11 D	E	M	O	N	■	12 C	L	A	V	I	U	S
E	■	■	■	I	■	R	■	■	■	O	■	■
13 R	U	14 P	E	S	■	O	■	15 C	E	T	U	16 S
■	■	E	■	■	■	N	■	A	■	■	■	I
17 M	E	T	O	18 N	I	C	■	19 L	Y	20 M	A	N
E	■	Z	■	U	■	E	■	O	■	O	■	N
21 R	A	V	E	N	■	22 T	O	R	O	N	T	O
A	■	A	■	K	■	I	■	I	■	G	■	T
23 K	E	L	V	I	N	■	24 A	S	C	E	N	T

THE ROYAL ASTRONOMICAL SOCIETY OF CANADA

NATIONAL OFFICERS AND COUNCIL FOR 2003-2004/CONSEIL ET ADMINISTRATEURS NATIONAUX

Honorary President	Roy Bishop, Ph.D., Halifax
President	Peter Jedicke, London
1st Vice-President	Scott Young, B.Sc., Winnipeg
2nd Vice-President	Dave Lane, Halifax
Secretary	Kim Hay, Kingston
Treasurer	David Clark, London
Recorder	Heide Debond, Toronto
Librarian	Robert Garrison, Ph.D., Toronto
Past Presidents	Rajiv Gupta, Ph.D., Vancouver and Robert Garrison, Ph.D., Toronto
Editor of *Journal*	Wayne Barkhouse, Ph.D., Halifax
Editor of *Observer's Handbook*	Rajiv Gupta, Ph.D., Vancouver
Editor of *Beginner's Observing Guide*	Leo Enright, Kingston
Editor of *Observer's Calendar*	Rajiv Gupta, Ph.D., Vancouver
Executive Secretary	Bonnie Bird, M.L.Sc., 136 Dupont Street, Toronto ON M5R 1V2 Telephone: (416) 924-7973

CENTRE ADDRESSES/ADRESSES DES CENTRES

The most current contact information and Web site addresses for all Centres are available at the Society's Web site: **www.rasc.ca**

Belleville Centre
9 South Park Street, Belleville ON K8P 2W9

Calgary Centre
C/O Calgary Science Centre, PO Box 2100 Station "M", Calgary AB T2P 2M5

Charlottetown Centre
C/O Clair Perry, 38 Mt Edward Road, Charlottetown PE C1A 5S2

Edmonton Centre
C/O Edmonton Space & Science Centre, 11211 – 142 Street
Edmonton AB T5M 4A1

Halifax Centre
PO Box 31011, Halifax NS B3K 5T9

Hamilton Centre
PO Box 1223, Waterdown ON L0R 2H0

Kingston Centre
PO Box 1793, Kingston ON K5L 5J6

Kitchener-Waterloo Centre
C/O John Beingessner, 479 Cabot Trail, Waterloo ON N2K 3Y3

London Centre
PO Box 842 Station B, London ON N6A 4Z3

Moncton Centre
C/O Dr. Francis LeBlanc, Département de physique et d'astronomie,
Université de Moncton, Moncton NB E1A 3E9

Centre francophone de Montréal
Casier postal 206 Station St-Michel, Montréal QC H2A 3L9

Montreal Centre
PO Box 1752 Station B, Montreal QC H3B 3L3

Niagara Centre
PO Box 4040, St Catharines ON L2R 7S3

Okanagan Centre
PO Box 20119 TCM, Kelowna BC V1Y 9H2

Ottawa Centre
PO Box 33012, 1363 Woodroffe Ave, Ottawa ON K2C 3Y9

Prince George Centre
7365 Tedford Road, Prince George BC V2N 6S2

Centre de Québec
2000 boul Montmorency, Québec QC G1J 5E7

Regina Centre
PO Box 20014 Cornwall Centre, Regina SK S4P 4J7

St. John's Centre
C/O Randy Dodge, 206 Frecker Dr, St. John's NL A1E 5H9

Sarnia Centre
C/O Jim Selinger, 160 George Street, Sarnia ON N7T 7V4

Saskatoon Centre
PO Box 317 RPO University, Saskatoon SK S7N 4J8

Thunder Bay Centre
286 Trinity Crescent, Thunder Bay ON P7C 5V6

Toronto Centre
C/O Ontario Science Centre, 770 Don Mills Road, Toronto ON M3C 1T3

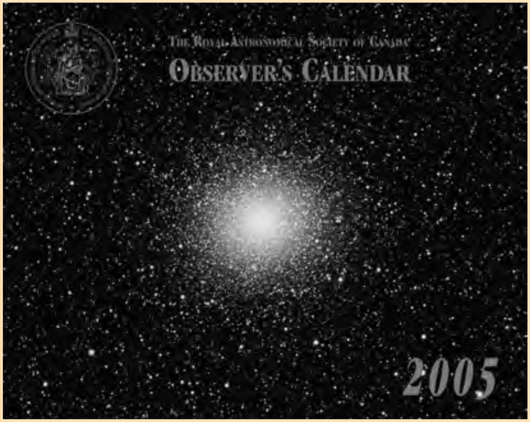
Vancouver Centre
C/O The HR Macmillan Space Centre, 1100 Chestnut Street
Vancouver BC V6J 3J9

Victoria Centre
C/O Lauri Roche, 8581 Sentinel Place, Sidney BC V8L 4Z8

Windsor Centre
C/O Ken Garber, 2831 Alexandra Avenue, Windsor ON N9E 2J8

Winnipeg Centre
PO Box 2694, Winnipeg MB R3C 4B3

Publications and Products of
The Royal Astronomical Society of Canada

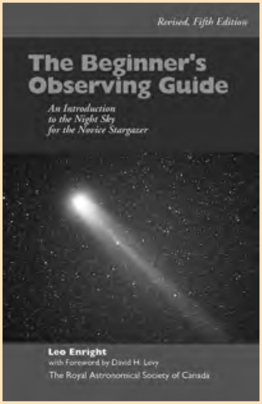


Observer's Calendar — 2005

The award-winning RASC Observer's Calendar is your annual guide

Created by the Royal Astronomical Society of Canada and richly illustrated by photographs from leading amateur astronomers, the calendar pages are packed with detailed information including major lunar and planetary conjunctions, meteor showers, eclipses, lunar phases, and daily Moonrise and Moonset times. Canadian and US holidays are highlighted. Perfect for home office or observatory.

Individual Order Prices:
$16.95 Cdn/ $13.95 US
RASC members receive a $3.00 discount
Shipping and handling not included.



The Beginner's Observing Guide

Extensively revised and now in its fifth edition, The Beginner's Observing Guide is for a variety of observers, from the beginner with no experience to the intermediate who would appreciate the clear, helpful guidance here available on an expanded variety of topics: constellations, bright stars, the motions of the heavens, lunar features, the Aurora, and the Zodiacal Light. New sections include: lunar and planetary data through 2010, variable star observing, telescope information, beginning astrophotography, a non-technical glossary of astronomical terms, and directions for building a properly scaled model of the solar system.

Written by astronomy author and educator, Leo Enright, 200 pages, 6 colour star maps, 16 photographs, otabinding.

Price: $19.95 plus shipping & handling.

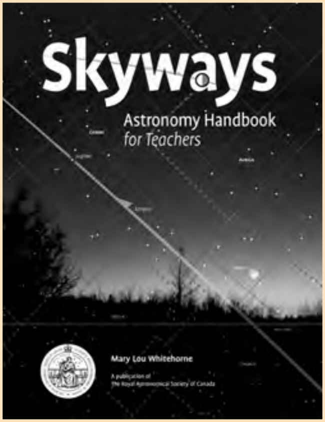
Skyways: Astronomy Handbook for Teachers

Teaching Astronomy? Skyways Makes it Easy!

Written by a Canadian for Canadian teachers and astronomy educators, Skyways is Canadian curriculum-specific; pre-tested by Canadian teachers; hands-on; interactive; geared for upper elementary, middle school, and junior-high grades; fun and easy to use; cost-effective.

Skyways is complete with conceptual background; teacher information; student worksheets; resource lists; Canadian contributions to astronomy section FAQ's; and more. Written by Canadian author and RASC member, Mary Lou Whitehorne.

Price: $16.95 Cdn (members); $19.95 Cdn (non-members)
(includes postage and handling; add GST for Canadian orders)



Shop On-Line at www.store.rasc.ca

Send cheque or money order to: RASC, 136 Dupont St, Toronto ON M5R 1V2 Canada
Please allow 6-8 weeks for delivery. Orders outside Canada please remit in U.S. Funds.
Major credit cards accepted. Call the National Office toll-free at 1-888-924-7272 to place your order.
(These products may also be available directly from your local Centre)