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A Tribute to the Life and Science of J. Mayo Greenberg

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1. A FULL RICH LIFE ...

J. Mayo Greenberg played a critical and unique role in the interstellar dust field by making fundamental contributions, establishing the study of interstellar dust as a modern scientific discipline and in defining its direction. He was present at the beginning of the modern era, writing a chapter entitled "Interstellar Grains" in Volume 1 of Annual Reviews of Astronomy and Astrophysics in 1963. He organized the first of these international conferences on dust, "Interstellar Grains", in August, 1965. He was influential in giving early focus to the field by drawing a handful of isolated workers and activities together and he participated fully as it grew to the multi-disciplined scientific enterprise represented by this meeting. In the Introduction to the proceedings of the first conference Mayo wrote, "It was hoped that such a scientific confrontation would result in a higher level of understanding and would consequently stimulate and coordinate future work in this field." It certainly did. Twenty one talks out of the 42 presented this week in Colorado are on topics Mayo chose for that first meeting. Thirty three percent of the speakers at this meeting were Mayo's students and postdocs or their students and postdocs. Several of the senior participants of this meeting have stated that the first scientific conference they attended was one of Mayo's early meetings on dust, and it was that meeting that defined much of their future scientific direction. It isn't much of an exaggeration to say that many of the participants here can find the roots of their research in a paper, a book chapter, a meeting discussion, or news story that Mayo wrote or presented some time ago. As one of our close colleagues put it, "No matter what we are working on, we often find Mayo has been there before us."

The breadth of his scientific interests and contributions was exceptional. Mayo was a different kind of player in a field in which, to this day, the knowledge gained in one wavelength region still remains largely uncoupled with the knowledge gained in another wavelength region and where specialists in one subdiscipline are unable to integrate the latest results from another. Mayo merged and integrated ideas and disciplines into a coherent picture. He saw the big picture decades before most people even realized there was a picture.

All this was accomplished not by single-minded focus, but as part of a full, diverse, and rich life, an exuberant life shared with many and of those many, numbers one through five always were Naomi and their four children (Figure 2).



Figure 1. Mayo at the Raymond and Beverly Sackler Laboratory Dedication, Leiden 1999.



Figure 2. Mayo and Naomi in Erice, Sicily, 1994.



Figure 3. Johann van der Waals (left), Henk van de Hulst (center) and Mayo (right) at one of the parties at the Greenberg home on the Rhine (1983).

Absolutely central to Mayo and foundational to all he was able to accomplish was his marriage to Naomi and his role as a father. Naomi summarized it this way. "We had it made. I always compared our relationship to a binary star system: I was the one that you couldn't see but exerted the pull that kept the system moving-he was the one that shone; a great combination." Mayo and Naomi's hospitality and generosity were legendary. Participants and speakers at Leiden's astronomy symposia were often invited to a wonderful dinner and unforgettable evening at the Greenberg's home on the Rhine (Figure 3). Naomi participated in many symposia with Mayo, often treating participants to evening recitals and organizing tours for family and friends during the sessions.

Mayo's exuberance, sense of humor, and love of life highlighted many a meeting-scientific and otherwise. Of the many examples to choose from we mention one of his visits to California. At that time Mayo rented a convertible "for the children" (Figure 4). Of course we never asked the age of the "children".

2. . . . and a life of science

Here we present a summary of Mayo's professional "highlights". But what can we choose as highlights and milestones? Many of those listed in Table 1 could be replaced several times over with others equally significant.

Mayo was born on January 14, 1922 in Baltimore, Maryland. A very bright young man with extraordinary gifts in mathematics, he entered Johns Hopkins University at 15 years of age and graduate school two years later. Mayo's grad-



Figure 4. Mayo preparing to take the "children" for a ride (San Jose, California, 1985).

uate career was interrupted by World War II when he went to work at Langley Field, Virginia on modeling airflow over wing surfaces. After the war Mayo married Naomi Sloven in 1947.

Upon his return to graduate school, Mayo started work on the theory of light scattering by small particles, work which he expanded through his postdoctoral years at The University of Maryland. From there Mayo took a teaching position at Rensselaer Polythechnic Institute (RPI) in Troy, New York and it was there that his interests turned to astronomy.

During the 60's, Mayo spent two sabbatical years at Leiden working closely with Henk van de Hulst to apply the new developments of scattering theory to the problem of interstellar dust. In the 1940's, van de Hulst and Jan Oort had expanded the notion of interstellar dirty ice grains to include formation and growth and applied these ideas to interpret scattering and extinction measurements. Mayo took up the challenge of extending the scattering models beyond the idealized spherical particle case. Scattering from non-spherical particles was necessary to simultaneously explain interstellar scattering *and* polarization measurements. This was particularly challenging in these pre-computer days.

And so was born Mayo's first foray into developing a laboratory analog approach to intractable astronomical problems. Working with Norman Peterson, Mayo developed the Microwave Scattering Laboratory in New York. Here, using microwave radiation and appropriately scaled particles of various sizes and shapes, they were able to experimentally tackle the intractable problem of understanding the scattering properties of non-spherical particles.

Table 1. J. Mayo Greenberg - Some Milestones

1947	Married Naomi Sloven. Mayo and Naomi Greenberg were married 54 years at the time of his death. They have four children with a wide range of interests and a deep love of classical music.
1948	PhD from Johns Hopkins University on the theory of radiation scattering.
	Postdoctoral positions at the University of Delaware and the University of Maryland.
1952	Assistant Professor at Rensselaer Polytechnic Institute (RPI), quickly rising to Full Professor.
1961	Sabbatical year at Leiden University.
1962-1967	Focus broadened from theoretical to experimental studies which led to the creation of the RPI microwave laboratory to measure the scattering properties of small particles.
1968	Visiting Professor at Leiden University.
1970	Chair Physics and Astronomy Department at the State University of New York, Albany 1970.
	The Physics and Astronomy Departments at Leiden University create a joint Laboratory Astrophysics "Work Group" and Professors Chair.
1975	Mayo accepts offer to fill this chair and moved to Leiden.
	Mayo's interest and vision guided the research in this laboratory on the optical properties of interstellar dust and ice analogs, astrochemistry, and laid the foundations of astrobiology. Mayo vigorously applied these results to cometary and other Solar System ices.
1992	Mayo retired but remained scientifically as active and involved as ever.
1989-1997	Director of the NATO International School of Space Chemistry.
1998	The American Philanthropists Raymond and Beverly Sackler create the Raymond and Beverly Sackler Laboratory for Astrophysics at Leiden, (http://www.strw.leidenuniv.nl/ lab/index.html) assuring the lab's future.
Nov.29, 2001	Mayo died at his home in Leiden.
2002	J. Mayo Greenberg Scholarship Prize founded to bring students from a developing country to study at Leiden. (http://www.strw.leidenuniv.nl/news/greenbergprize.php)

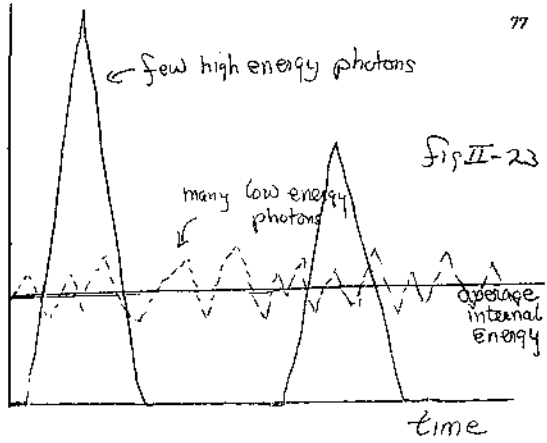
Mayo had over 300 publications, with 146 from his Leiden years alone. A period of his life he started at the age of 53.

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Another significant fact regarding grain temperature which has not been sufficiently considered concerns the basic definition of temperature. The equilibrium temperature of a system may be defined only if the fluctuations of system energy are small compared with the average. We should compare the average energy per absorbed photon (or the rate of absorption of radiant energy) with the total heat content of the grain. The heat content of a grain is given by (see, for example, Kittel [1956], p. 130)

$$Q \approx 60N(kT_g)(T_g/\Theta)^3 \tag{40}$$

where Θ is the Debye temperature and N is the total number of atoms (or molecules) in the grain. Using $\Theta = 300$ and $N = 4 \times 10^{10}$ (for radius $a = 10^{-4}$ cm), we get $Q = 9 \times 10^{-3}$ erg for $T_g = 10°$ K. This is approximately 100 times the rate of radiant energy input (and output) of 5.2×10^{-10} erg/sec. For $a = 10^{-5}$ cm, $Q \approx 9 \times 10^{-11}$ erg and $(dE/dt)_{rad} \approx 10 \times 10^{-11}$ erg/sec, and the temperature is still definable. For $dE/dt = 10^{-12}$ erg/sec, this is equivalent to one photon of wavelength $\lambda = 2\ \mu$ per second. In view of the fact that $Q/(dE/dt) \propto aT_g^4$, it is possible to find conditions under which this ratio is of the order of unity, and the concept of a grain temperature is then not meaningful.



In the latter case the internal energy is never too far from the average value and we are justified in characterizing the mean energy by a temperature. In the former case, however, the grain's actual internal energy is generally near zero, with occasional very high peaks. In this case speaking of a temperature does not make sense.

Figure 5. Top - Text adapted from Mayo's 1968 paper "Interstellar Grains". Bottom - Mayo's 1963 RPI lecture notes describing "temperature" fluctuations in small grains. This process was not observed until 16 years later.

From this time forward, Mayo played a pivotal and foundational role in our field. His classic 140 plus page article entitled simply "Interstellar Grains", published in 1968 is still one of the most complete treatments of the subject that can be found anywhere. This thorough analysis of the physics and chemistry of grains of various shapes and types (metals, graphite, dirty ice, graphite core-ice mantle) and their scattering and polarization properties was must reading for researchers in this field for years. Here Mayo derived an excellent panspectral match to the extinction curve constraining interstellar grain composition, size, and shape. This major paper also includes some gems. The short description of the meaning of grain temperature and stochastic excitation given on page 258 is one of them (Fig. 5, top). To the best of our knowledge, this is the first recognition and published treatment of this phenomenon. Mayo wrote, "the concept of grain temperature is ... not meaningful" when individual photons highly excite small grains (single large molecules) to above average energies. Figure 5 (bottom) shows Mayo's notes on this from his 1963 class at RPI (reproduced from Li, 2004). In 1983 IRAS, the first infrared astronomical satellite, discovered strong, unexpected emission from the diffuse galactic sky at 12 and 25 microns. This emission arises from precisely the type of process Mayo described in 1963 to his class at RPI. This process accounts for over 30% of the total galactic infrared emission, a good part of which is contained in the ubiquitious interstellar PAH emission spectrum.

With the discovery of simple interstellar molecules such as CO and H_2CO about 1970, Mayo and his colleagues put forth the radical idea that ice grains played an intimate role in astrochemistry (Figure 6). The resistance to this idea from the interstellar chemistry community was strong for many years. It is only over the past 15 years that the interstellar chemistry community has recognized the important role of icy grain mantles.

It was about this time, at 53 years of age, an age at which many are starting to think of retirement, Mayo and Naomi Greenberg moved to Europe for Mayo to accept the Chair of Laboratory Astrophysics at Leiden University (Figure 7). As he had approached the problem of scattering from non-spherical grains a decade earlier, Mayo, a theoretical astrophysicist, felt laboratory data were sorely needed to test and guide the various theories on interstellar dust composition and their role in astrochemistry. It had again become impossible to gauge the merits of the competing theories on the basis of observations and theory alone.

As an interviewee for the Assistant Professorship position of experimental laboratory astrophysicist in this group, LJA met Mayo in 1975. Mayo was seeking someone to work with Fred Bass and develop an experimental program to measure the properties of interstellar materials under realistic conditions. With a Ph.D. and postdoctoral experience in low temperature spectroscopy and energy transfer, LJA was very interested in helping to start this group and was awarded the position. We had a very fruitful seven years together. In looking back, this was the first time the argument was made that significant progress would be possible in our field only when observational, theoretical, and targeted experimental data were all brought to bear on the problems at hand. This is now the standard approach to tackling problems related to the composition of interstellar matter, yet back in those days its importance wasn't appreciated. It

EXPLODING INTERSTELLAR GRAINS AND COMPLEX MOLECULES

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Abstract. The triggering of an explosive chemical reaction in a grain which consists of free radicals frozen in a matrix of photolyzed dirty ice material is seen as a possible source of complex interstellar organic molecules.

1. Introduction

The interstellar dust appears to play a critical role in the formation of the interstellar molecules. As is shown elsewhere in this volume the rate of formation of complex molecules directly out of the gas fails by orders of magnitude to compete with the rate of destruction in maintaining the observed abundances. Exactly what the mechanism of molecule production via dust may be is not clearly defined. But it seems clear that the chemical and physical character of the dust are critical in distinguishing between the relative importance of the various conceivable processes.

The distribution of the molecules under consideration is sufficiently far removed from stars that they can only have reached the regions in times much larger than their typical decay times as determined by the ultraviolet (or other disruptive) radiation.

A molecule with a radiative life limited to 100 yr in a radiation field like that suggested by Habing would travel, at a speed of 10 km s^{-1}, a distance of merely 10^{-3} pc before being destroyed. The existence of reasonably complex molecules well beyond this distance from the center of dark clouds seems to preclude the likelihood of their formation in the atmosphere of protostars.

Molecules may be formed on or in grain surfaces. The surface phenomenon has been a subject of both theoretical and experimental studies (Breuer, 1973). The possibility of molecules being an intrinsic part of the grain and appearing in space as the result of some grain disruption process or event is the focal point of this investigation. Both laboratory as well as theoretical investigation bearing on this process are considered.

2. Radiation Effects on Dust

For our basic dust model we consider those interstellar grains which have formed by

Figure 6. Title page from Mayo's 1973 article with Andrew Yencha exploring the potential role interstellar ices might play in astrochemistry. The interstellar molecules H_2CO and CO had only been discovered in 1969 and 1970 respectively.

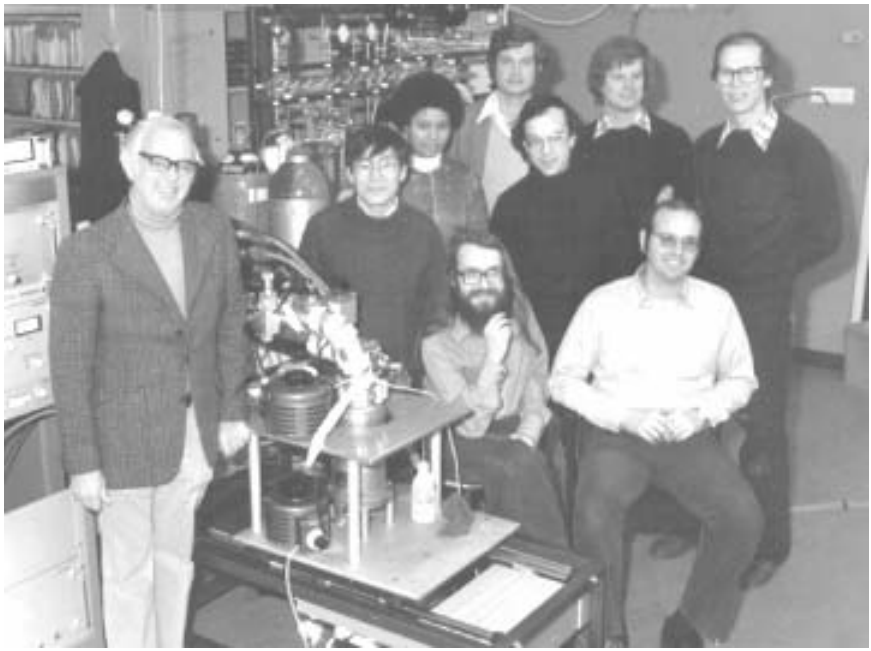


Figure 7. The founding members of the Laboratory Astrophysics Group, Leiden-1977. Clockwise, left to right. Mayo Greenberg, Seung Soo Hong, Lena Cientja, Colin Norman, Cyp van de Bult, Fred Baas, Wim Hagen, Lou Allamandola, Xander Tielens.

was Mayo's early recognition of this, his willingness to gamble his career on it, and his raw tenacity for years before (and over the years hence) that confronted and ultimately led our field to accept this as one of its fundamental tenets.

In 1979, Ld'H joined the group as a young and timid (!) graduate student. He was given the task to characterize the photochemistry of UV processed interstellar ices and explore the experimental conditions necessary to store chemical energy within these ices. This work showed it was possible to store sufficient chemical energy within these ices to drive explosive desorption of interstellar grain mantles, validating Mayo's theoretical work with Andrew Yencha ten years earlier (Figure 6).

With Mayo's guiding ideas, the laboratory group laid the foundation and developed many of the ideas central to our understanding of interstellar ice. Mayo integrated these results and prominently applied them to other areas: comets, astrochemistry, and bioastronomy. Over the years this laboratory has provided fruitful ground to roughly 20 graduate students and 10 postdoctoral researchers. In keeping with the philosophy of providing unique laboratory data to understand new observations, this laboratory, now titled the Raymond and Beverly Sackler Laboratory for Astrophysics, is focusing on ice surface chemistry.



Figure 8. Mayo at the conference "Physics and Composition of Interstellar Matter" organized by Jacek Krelowski in Bachotek, Poland in 1990. J. Krelowski is speaking.

Mayo continued to work in all of these areas, and at the frontier, his entire life. He has regularly "shown the way" and was often years ahead of the majority of researchers in the field. Quoting David Block (2003), "He did not develop theories to explain existing observations; rather, Mayo developed models and predicted scores of observations." During the late 80's and early 90's he and his students expanded these scattering models to treat fluffy grains with fractal analysis and applied this to comet science. Mayo's desire, confidence, and tenacity to do a job in spite of the computational and conceptual difficulties were his trademark. He had the unique gift of seeing the simple physics behind a problem and getting directly to the core questions. Perhaps this is partly why some of his ideas were not readily accepted. Being a competitor, Mayo would defend his ideas with simple arguments and emotion. While many of us were sometimes irritated by Mayo's laughingly pointing out "I had that idea over twenty years ago!", it was also too often true and, at times, was also the very provocation that pushed us forward. Mayo's insatiable curiosity and broad competencies laid so many foundations in so many different areas that his influence is sometimes difficult to trace, but a careful analysis of his publications and lectureships reveal that, throughout his long career, he has been a fountainhead of new ideas that have been taken up by the community. Mayo brought a unique and powerful combination of richness, energy, breadth, and enthusiasm to his work that eludes the simple categorization and quantification of which scientists can be so fond.

Those of us who worked closely with Mayo came to appreciate his tireless dedication to science on a global scale (Figure 8). He collaborated with researchers around the world and generously brought in and taught their stu-


15 75

MARE

Leidse Werkgroep ontdekt organisch materiaal in de ruimte tussen de sterren

Mogelijke doorbraak in ons denken over het ontstaan van biologisch leven

Quirien van Koolwijk

Figure 9. Mayo launched astrobiology 20 years before the word was coined. This Leiden student newspaper article headline from 1980 reads "Possible breakthrough in our thinking about the origin of biological life" . Figure 10 shows Mayo could even stir up the normally staid Dutch press.

dents. He stimulated, fostered and encouraged research at institutes around the world. Each of these continues to produce new generations of scientists. The countries from which the first nine members of the Astrophysics Laboratory Workgroup (Figure 7) hailed illustrate Mayo's international reach: Australia, Curacao, Korea, The Netherlands, and The United States of America. Over the next few years France, China, Germany, Egypt, and Mexico were added to this list.

Mayo's impact on our field and exceptional contributions have been felt by many at all stages in their careers. Some measure of the depth of Mayo's influence and the degree of the community's appreciation is reflected by the lectureships, scholarships, and tributes to Mayo authored by scientists from around the world whose lives and careers he fundamentally touched (e.g., Marcus, 2001; Block *et al.* 2003; Li 2003). Leiden University will publish a book dedicated to Mayo's memory. This legacy will continue under the auspices of the J. Mayo



EXPERIMENTEN IN LEIDEN

Begin kosmisch leven nagebootst

Aminogroepen in kunstmatige „stofwolken"

Levend materiaal in heelal

achtergrond

LEIDSE COURANT MAANDAG 15

Leidse onderzoekers vinden leven tussen de sterren

Figure 10. Articles from the Leiden newspapers: Leidse Volkskrant (8/15/1980), Leidse Courant (8/16/1980), and Haarlem's, Haarlems-dagblad (8/18/1980). The headlines read: "The beginning of cosmic life mimiced", "Leiden researchers find life between the stars", and last, but certainly not least, "Living material in the heavens." This is a small sampling of the articles which appeared internationally, and throughout the major Dutch papers in Amsterdam, Rotterdam and The Hague. Working with Mayo was anything but dull!

Greenberg Scholarship Prize, a scholarship which will bring students from developing countries to study at Leiden.

Remarkably, many of the things we are discussing today, and will be discussing for some time in the future, Mayo already saw in the 1960's. About 40 years ago, at a time when dust wasn't considered important to most astrophysicists, a decade before interstellar CO and H_2CO were discovered, Mayo was writing about refractory core-ice mantle grains. About 30 years ago he invoked those grains as key participants in the emerging field of astrochemistry when only the simplest of molecules imaginable, CO and H_2CO, *were* discovered in the ISM. Not stopping here, in 1980 Mayo caused quite a stir in the press when he speculated that grain chemistry could produce complex organic molecules, including potential biogenic species (Figures 9,10). Each of these predictions predated their acceptance by one to two decades.

Now, following almost four decades of detailed observations and theoretical modeling of interstellar gas phase molecules, the central role interstellar grains play in astrochemistry is widely recognized. Solid state chemical processes such as gas/surface interactions, and energetic processing by UV photons and cosmic rays directly influence the make-up of the interstellar gas and determine the

nature of the complex, non-volatile organic molecules that seed young planetary systems.

Mayo was a visionary, a pioneer, a creative force in the dust field. It was odd to attend this meeting on dust without Mayo's enthusiastic presence, but given that 17 of the 45 speakers are Mayo's direct academic descendents, his ideas are present. We close with a quote from one of the organizers, "Mayo Greenberg started the Dust field in astrophysics when very few people were thinking of dust and astrophysics. As a single individual, he probably influenced the dust field more than any other individual." We in this field are exceedingly grateful for all his contributions.

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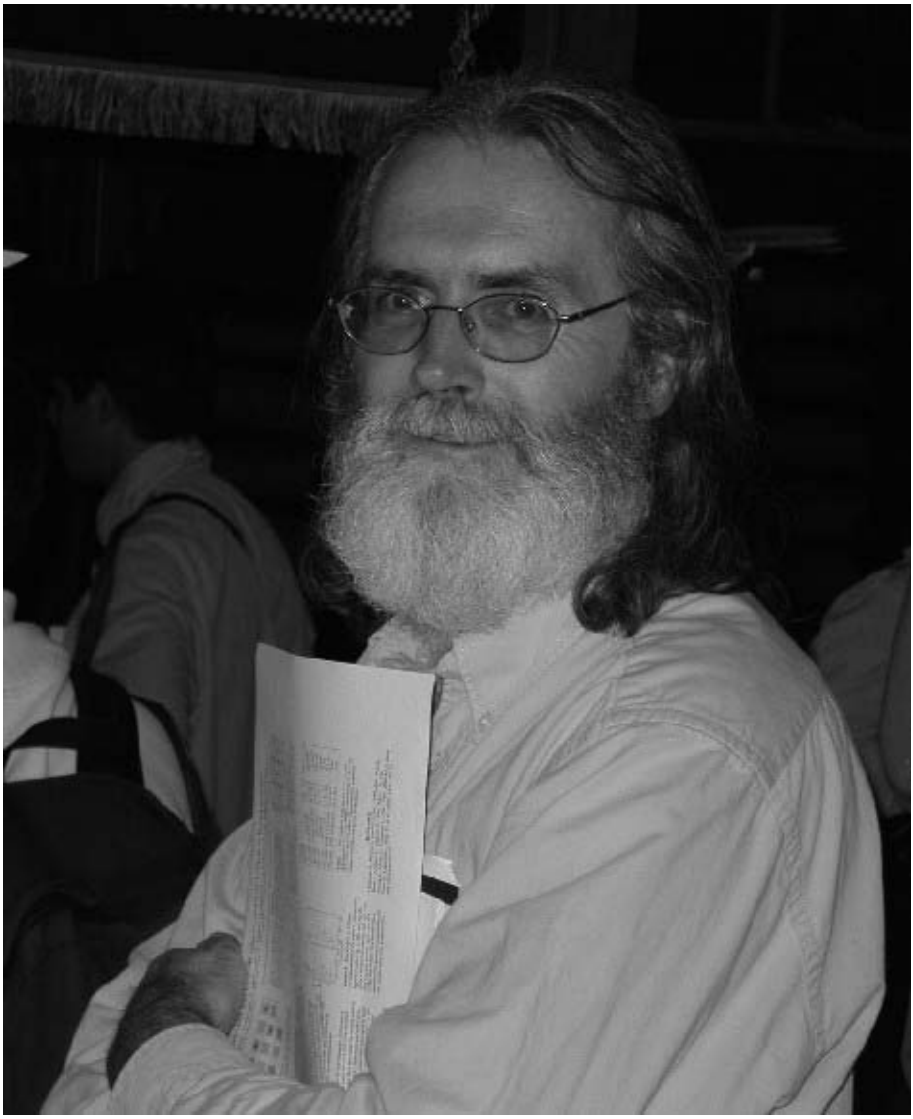
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Peter G. Martin. Photo credit: Ted Snow.