

# Faculty Development Leave Proposal

*Two Studies in Theoretical Astrophysics:  
Cosmic-Ray Production in Supernova Remnants  
and  
Estimating the Fraction of Solar Systems with Habitable Planets*

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Principal Faculty since fall, 2000 (4<sup>th</sup> year)  
Requested Leave: Fall Semester 2004  
Previous Summer Fellowship: Summer 2002

## ABSTRACT

I am requesting a Faculty Development Leave for the fall semester of 2004 to work on two research projects which I am currently involved in. The first project, done in collaboration with Fulvio Melia of The University of Arizona, involves the theoretical study of cosmic-ray production and subsequent radio and gamma-ray emission in supernova remnants interacting with molecular clouds in the interstellar medium. The second project, done in collaboration with Fred Adams of The University of Michigan, involves the theoretical study of the stability and habitability of Earth-like planets in other solar systems. Both projects represent ongoing works that have yielded three publications in the past two years, and have involved Xavier physics majors. My request for a faculty development leave is motivated by the recent submission of two proposals to NASA for funds to support research on these projects. A leave next fall would enable me to make substantial progress on the work outlined in these proposals, thereby ensuring their successful and timely completion. Since NASA proposals are judged in part by the investigators' performances on previously funded proposals, it is imperative for future projects that I meet my obligations to these collaborative works. Doing so will allow me to maintain my strong research ties with collaborators at major research Universities, and in turn, will lead to future research opportunities.

## I. Introduction

While I thoroughly enjoy teaching and am strongly committed to this task, I also find the ability to participate in active research in theoretical astrophysics very rewarding. This research has been facilitated by collaborations that I have developed over the past 15 years with Dr. Fulvio Melia of The University of Arizona and Dr. Fred Adams of The University of Michigan. Indeed, being at Xavier has allowed me to successfully re-establish research ties with Dr. Adams, and I now visit The University of Michigan on a nearly monthly basis.

Looking ahead to next 15 years of my career, I recognize the importance of maintaining good working relations with my present colleagues, and see the benefits of developing new ones. Given the teaching demands at Xavier, these ends will require an occasional leave from teaching duties to ensure that I can contribute significantly to these collaborations. For that reason, I am requesting a Faculty Development Leave for the 2004 fall semester.

This request comes at a crucial time in my career. Specifically, I am co-investigator in a proposal titled "*A Multi-wavelength Approach to the Study of Supernova Remnant Shells*" that was submitted to NASA earlier this summer (with Fulvio Melia of The University of Arizona and Farhad Yusef-Zadeh of Northwestern University). In addition, I am a scientific collaborator in a proposal titled "*Estimating the Fraction of Solar Systems with Habitable Planets: Effects of Companions on Dynamical Stability and Formation*", submitted to NASA earlier this summer by Dr. Fred Adams of the University of Michigan. These proposals outline work that my colleagues and I hope to complete over the next three years. A sabbatical next fall would allow me to build on next summer's efforts, thereby facilitating a good start to these projects, and in turn, helping to ensure their successful completion. This outcome is crucial for securing funds for future research,

as NASA proposals are judged in part by the investigators' productivity of previously funded projects. Even if these proposals are not funded, they outline the works that my collaborators and I have committed to over the next several years.

## **II. Rationale for Visiting The University of Cincinnati**

Given my family situation (three young children), I am not in a position at this time to relocate for an entire semester. I would therefore spend a significant amount of my time next fall at The University of Cincinnati. Specifically, I would hold the title of Visiting Faculty, have office space, internet and library access, and have use of office supplies. These arrangements have already been made with the Chair of the Physics Department at UC. I would then travel extensively to both The University of Michigan and The University of Arizona. Funding for these trips would come from the Joan G. McDonald Award (\$5,000) I received last Spring, and from the Hauck Foundation (this foundation provides research support to faculty in the physics department). In addition, I have requested funds for travel to The University of Arizona in the NASA proposal submitted with Fulvio Melia.

My motivation for visiting the University of Cincinnati stems from my desire to spend a semester at a nearby research University, and to benefit from the resources that such a University has to offer. More to the point, however, I have an interest in developing a research collaboration with Dr. Margaret Hanson of the physics department at UC, as her work in observational astronomy overlaps with my theoretical work on star formation theory. Dr. Hanson and I have already had some preliminary discussions about possible research projects. By being at UC, I have a real expectation that these projects will actually materialize. In turn, Dr. Hanson plans to take a sabbatical at Xavier University during the 2005-2006 academic year.

## **II. Proposed Research**

### **A. Cosmic-Ray Production in Supernova Remnants**

#### **1. Introduction**

Cosmic-rays are very high-energy particles (mostly protons) that populate our galaxy. While the origin of cosmic-rays remains an unresolved issue in astrophysics, it is generally believed that some of these highly energetic particles are produced in supernova remnants (SNRs). An important breakthrough toward resolving this issue came during the 1990's, when gamma-rays were detected coming from five of the several hundred of supernova remnants that have been observed in our galaxy. (It is now known that this small subset of supernova remnants are unique in that they are interacting with molecular clouds - relatively dense clumps of interstellar gas and dust.) Since these gamma-rays are produced by interactions between cosmic-rays and the SNR environments in which they are created, it is now possible to compare the results of detailed theoretical studies of cosmic-ray production and subsequent emission directly to observations.

Indeed, a significant amount of theoretical work on gamma-ray production from SNRs was completed in the late 1990's by several authors. However, these authors significantly underestimated the number of electrons and positrons produced when cosmic-rays interact with the gas contained within the supernova remnants, and as such, needed to invoke a separate population of highly-energetic electrons in order to match their theoretical results to the observations.

## 2. Recent Work

In the mid 1990's, gamma-rays were detected coming from the Galactic center. This region of our galaxy is quite unique in that it is anchored by a supermassive black hole (whose mass is 2.6 million times greater than that of our Sun), and contains an unusual supernova remnant known as Sagittarius A East (see Figure 1). However, if Sagittarius A East is the source of the gamma-rays detected from the Galactic center, then it produces about 100 times more gamma-rays than the five gamma-ray supernova remnants discussed above. In addition, the radio spectrum of Sagittarius A East is quite different from the radio spectra of the other five gamma-ray producing SNRs.

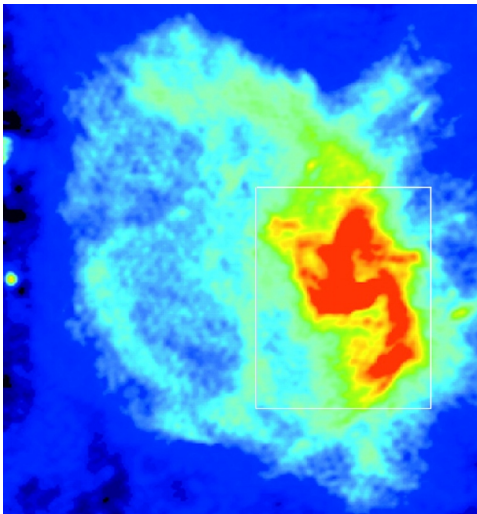


Figure 1 - A 6 cm radio map of Sagittarius A East is shown in light blue (false color). The red structure is known as Sagittarius A West, and is known to be molecular material that surrounds the supermassive black hole anchoring the Galactic center.

During the past few years, Fulvio Melia and I (along with several other members of our collaboration) have worked extensively on determining whether Sagittarius A East is indeed the source of the Galactic center gamma-rays, and if so, to reconcile the differences between this object and the other SNRs.

The results of our work (papers # 23, 24, 25 & 29 in the list of Publications below)

indicate that Sagittarius A East is the likely source of the gamma-ray emission observed from the Galactic center, and that what accounts for the unusually bright gamma-ray luminosity and unusual radio spectrum of this source is the unique high-density and strongly magnetized environment found at the Galactic center. In addition, our work also shows that authors who invoked a similar mechanism to account for the gamma-ray emission produced in SNRs significantly underestimated the number of electrons and positrons injected into the SNR environments. In contrast, we find that the injected electrons and positrons in Sagittarius A East are sufficient to account for all of the observations, thereby eliminating the need to postulate the presence of an additional high-energy electron population.

### **3. Proposed Work**

Based on the success of our work on Sagittarius A East, and given a wealth of recent and upcoming observations of the Galactic Center at several wavelengths, my colleagues and I recently submitted a proposal to NASA seeking support for our continued research in this area. This proposal outlines several calculations that we hope to perform over the next three years. The subset of these calculations that I am proposing to perform during my faculty development leave are outlined below. A timetable for the completion of this work is given in Section III, along with expectations for publications.

i - The mechanism invoked to account for the gamma-ray emission at the Galactic center presented above produces large numbers of positrons which must eventually annihilate with electrons. (In contrast, the electrons invoked by previous authors in their theoretical studies have no such counterparts.) This electron-positron annihilation process produces an unmistakable X-ray signature. Indeed, this signature has been observed both along the

galactic plane and toward the Galactic center. Up until recently, it has not been possible to pinpoint where this X-ray radiation was being produced, leaving fairly loose constraints on the nature of its origin. However, INTEGRAL, a recently launched satellite with the ability to spatially resolve the annihilation X-rays emission, will map the Galactic center, thereby providing important observational constraints. The proper interpretation of the INTEGRAL observations will be complicated by the fact that positrons must lose a significant amount of energy (cool) before they can annihilate, during which time they diffuse through the interstellar medium. In order to properly match the observations to our theory, we will model the cooling and diffusion of these particles, thereby producing a “theoretical” spatial map of what this emission will look like under different viable circumstances. These theoretical maps will then be compared to those obtained by INTEGRAL.

ii - One problem with the interpretation of cosmic-rays originating from SNRs is that standard models for cosmic-ray production in these environments do not seem to account for the highest energy cosmic-rays observed. However, Sagittarius A East is unique given its environment (which is why it outshines the other SNRs in gamma-rays by a factor of 100). Preliminary results by my colleagues at the University of Arizona suggest that Sagittarius A East could indeed be the source of the highest energy cosmic-rays. We therefore plan to undertake a more extensive study of cosmic-ray production in the Sagittarius A East environment.

## **B. Estimating the Fraction of Solar Systems with Habitable Planets**

### **1. Introduction**

The recent discoveries of extrasolar planetary systems have shown that our solar system is not unique. Specifically, planets roughly the size of Jupiter (which is about three hundred times more massive than the Earth) have now been detected to orbit nearly 100 distant stars. Although terrestrial planets have never been observed in extrasolar systems due to their small masses, they are expected to form in planetary systems that include Jupiter sized planets. Indeed, the probable existence of such planets underlies recent efforts to build a Terrestrial Planet Finder in the near future.

An important issue regarding the presence of Earth-like planets in the observed extrasolar planetary systems is whether or not their orbits will remain stable over cosmological and evolutionary times. When a single planet orbits a star, the resulting trajectory is stable, and the planet traces out an elliptical orbit around the star. However, the presence of an additional planet or star leads to a system that can become unstable, leading to the ejection of the smallest planet out of the system. As such, the discoveries of extrasolar planets have reinvigorated the investigation of the three-body problem within the context of planetary stability.

### **2. Recent Work**

A great deal of work, both analytical and numerical, has already been done on stability and the development of chaos in celestial mechanics. But many of the investigations regarding planetary stability have been relatively narrow in scope. Recently, Eva-Marie David (Xavier physics major), Fred Adams, Elisa Quintana (a graduate student at the University of Michigan) and I examined the three body problem in somewhat broader terms by considering the stability of

Earth-like planets orbiting a Sun-like star in the presence of a third “companion” with mass in the range between 0.001 to 0.5 solar masses. This mass range includes companions as small as Jupiter and as large as small stars.

The main result of this investigation was a determination of the ejection time for Earth-like planets over an extensive range of the companion's initial orbital trajectory (i.e., its eccentricity) and its initial distance of closest approach to the central Sun-like star (known as the periastron distance). The ejection time of an Earth-like planet was determined for a choice of the companion’s mass, eccentricity, and periastron. Our results show that the ejection time varies sensitively to the initial conditions picked (a characteristic of chaotic systems). That is, small differences in the starting conditions of the Earth-like planet or companion (with all other factors remaining the same) can lead to large difference in the ejection time. However, we found that the ejection time can be characterized in terms of a log-normal distribution (see Figure 2), and that the average of the log of the ejection time depends primarily on the mass and initial periastron distance of the companion.

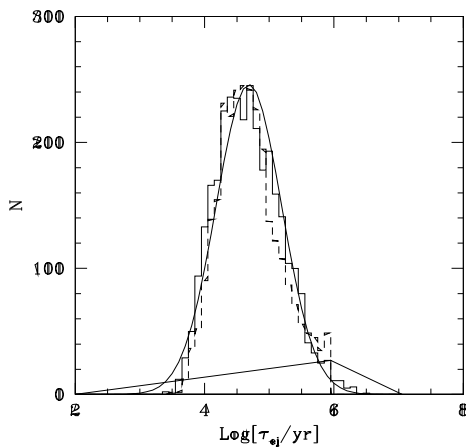


Fig. 2 - Distribution of ejection times for different realization (initial conditions) of the same system. The two histograms show the results from two separate integration codes. The smooth curve shows the lognormal distribution with the same peak value and width as the computed distributions.

One interesting application of this investigation concerns the possible habitability of extrasolar terrestrial planets. Approximately two-thirds of main-sequence stars (stars similar to our Sun) are in orbit with other, smaller stars. These companions can disrupt the orbit of an Earth. Although this issue has been explored by several groups, our numerical simulations shed further light on the subject. Specifically, these results indicate that just over half of the two-star systems populating our galaxy could also maintain a stable Earth-like orbit for at least 4.6 billion years (the age of our Earth).

Results of this work were published in the July 2003 issue of *The Publications of the Astronomical Society of the Pacific (PASP)*, in a paper titled “Dynamical Stability of Earth-Like Planetary Orbits in Binary Systems” by Eva-Marie David, Elisa Quintana, Marco Fatuzzo and Fred C. Adams. In addition, the results of our paper were presented by Eva Marie David at the 201<sup>st</sup> meeting of the American Astronomical Society (January 2003, Seattle), as well as at the Council on Undergraduate Research 2003 Posters on the Hill Session (April 2003, Washington D.C.) as one of sixty nationally selected student posters to be displayed on Capitol Hill. Matt Lijoi and Rich Gauvin (Xavier physics majors) continued this work during the Spring and Summer of 2003, with Matt working at The University of Michigan through a National Science Foundation program, and Rich working at Xavier with the support of a Hauck scholarship.

### **3. Proposed Work**

Based on the success of the work discussed above, and given the ongoing search for additional planetary systems, my colleague Dr. Fred Adams recently submitted a proposal to NASA seeking three years of support for our continued research in this area (I am listed as a

scientific collaborator on this proposal). This proposal outlines several calculations that we hope to perform over the next three years. The subset of these calculations that I am proposing to perform during my faculty development leave are outlined below. A timetable for the completion of this work is given in Section III, along with expectations for publications.

i - We plan to continue our numerical investigation in the stability of Earth-like planets in orbit around Sun-like star in order to cover a much larger amount of possible parameter space (including relative inclination angles between the various orbits). This much broader data set will then allow us to better estimate the fraction of binary systems with Sun-like primaries that allow an Earth-like planet to remain stable for a specified time.

ii - We will apply this analysis to the observed planetary systems now being discovered in association with nearby stars. This analysis will allow us to say something more definitive about the prospect of finding habitable planets in nearby extrasolar systems.

### **III. Timetable and Expected Publications for Proposed Research**

June - August 2004

- Begin work on determining the electron-positron cooling and annihilation occurring in Sagittarius A East (II.A.3.i).
- Run simulations of three-body problem to survey a large amount of parameter space for the Earth-like case (II.B.3.i).

#### September 2004

- Use the results of summer work on electron-positron cooling and annihilation to make maps of annihilation radiation for the Galactic center under viable scenarios (II.A.3.i).
- Compile results of numerical simulation of three body problem, and attempt to use this extensive data set to built a stochastic model of this process (II.B.3.i).

#### October 2004

- Write and submit (to *The Astrophysical Journal*) an article on the annihilation radiation expected from the Galactic center (II.A.3.i).
- Begin work on a detailed analysis of high-energy cosmic-ray production in Sagittarius A East (II.A.3.ii).
- Complete analysis of three-body problem (II.B.3.i)

#### November 2004

- Write and submit an article (to *The Publications of the Astronomical Society of the Pacific*) on the three-body problem analysis (II.B.3.i)
- Begin work on the analysis of planetary systems now being discovered (II.B.3.ii)

#### Spring semester 2005

- Write and submit (to *The Astrophysical Journal Letters*) an article on the high-energy cosmic-ray production in Sagittarius A East (II.A.3.ii).
- Write and submit (to *The Publications of the Astronomical Society of the Pacific*) an article on the analysis of the planetary systems now being discovered (II.B.3.ii).

#### **IV. Brief Biographical Sketch of my Colleagues**

Dr. Fulvio Melia is a full professor in both the physics and astronomy departments of The University of Arizona. He is also the associate head of the physics department. Dr. Melia has received numerous awards during his professional career, including a Presidential Young Investigator Award, an Alfred P. Sloan Fellowship, a Sir Thomas Lyle Fellowship, and a Miegunyah Fellowship. Dr. Melia is the author of one textbook and two popular books.

Dr. Fred Adams is a full professor and associate chair of physics at The University of Michigan. Dr. Adams has received numerous awards during his professional career, including a National Science Foundation Young Investigator Award, a Robert J. Trumpler Award, a Helen B. Warner Prize, and an Excellence in Research Award. Dr. Adams is the author of two popular books.

## V. Biographical Sketch

### Education

- Ph.D. Physics, Northwestern University, 1991  
B.S. Physics and Mathematics, St. Olaf College, 1987

### Experience

- 2000- Assistant Professor of Physics, Xavier University  
1997-2000 Lecturer, University of Arizona  
1994-1997 Assistant Professor of Physics, Wesleyan College (GA)  
1992-1994 NASA Compton Gamma Ray Observatory Postdoctoral Fellow, Univ. of Michigan  
1991-1992 Research Fellow, University of Michigan

### Honors and Awards

- 2003 Joan G. McDonald Award, Xavier University  
1999 College of Arts and Sciences Distinguished Teaching Award, University of Arizona  
1999 Alpha Delta Pi Recognition for Outstanding Education, University of Arizona  
1998 Alpha Delta Pi Recognition for Outstanding Education, University of Arizona  
1997 Vulcan Materials Company Teaching Excellence Award, Wesleyan College  
1996 Student Government Service Award, Wesleyan College  
1987 Departmental Distinction in Physics, St. Olaf College  
1985-87 Sigma Pi Sigma Membership, St. Olaf College

### Fellowships and Grants

- 2003 Hauck Summer Research Grant, Xavier University  
2002 NSF Step Grant (Co-PI), Xavier University  
2002 Summer Fellowship, Xavier University  
2001 NSF Instrumentation Grant (Co-PI), Xavier University  
2001 Graham Initiative Grant, Xavier University  
2001 Hauck Summer Research Grant, Xavier University  
2000 Hauck Summer Research Grant, Xavier University  
1992-94 NASA Compton GRO Postdoctoral Fellowship, University of Michigan  
1988-90 University Fellowship, Northwestern University

### Undergraduate Research Students

- 2001: Nicole Allen, Eva-Marie David, Hans Spaeth  
2002: Joe Brinkman, Eva-Marie David, Julie Langenbrunner, Elizabeth Leicht, Kevin McGrath, Hans Spaeth, Greg Wiggers  
2003: Eva-Marie David, Rich Gauvin, Julie Langenbrunner, Elizabeth Leicht, Matt Lijoi, Greg Wiggers

## Publications in Refereed Journals

1. Gamma-Ray Emission in the Magnetospheres of Neutron Stars with Accretion Disks, F. Melia and M. Fatuzzo, *The Astrophysical Journal*, 346: 378-390, 1989.
2. Transverse Conductivity of a Relativistic Plasma in Oblique Electric and Magnetic Fields, F. Melia and M. Fatuzzo, *Physical Review D*, 43: 319-331, 1991.
3. Computing the Normalized Dirac Wave Function for Oblique Electric and Magnetic Fields, F. Melia and M. Fatuzzo, *Nuovo Cimento*, 106B: 253-261, 1991.
4. Relativistic Charge Currents in Oblique Electric and Magnetic Fields, F. Melia and M. Fatuzzo, *Journal of Plasma Physics*, 45: 415-425, 1991.
5. Transverse Conductivity of a Relativistic Plasma in Oblique Electric and Magnetic Fields, F. Melia and M. Fatuzzo, *The Astrophysical Journal*, 373: 198-207, 1991.
6. Transient Particle Acceleration in Strongly Magnetized Neutron Stars, F. Melia and M. Fatuzzo, *The Astrophysical Journal*, 376: 673-677, 1991.
7. Transient Particle Acceleration in Strongly Magnetized Neutron Stars. II. Effects Due to a Dipole Field Geometry, M. Fatuzzo and F. Melia, *The Astrophysical Journal*, 382: 570-575, 1991.
8. Gamma-Ray Bursts From Sheared Alfvén Waves, F. Melia and M. Fatuzzo, *The Astrophysical Journal (Letters)*, 383: L57-L60, 1991.
9. Gamma-Ray Bursts From Extragalactic Radio Pulsars, F. Melia and M. Fatuzzo, *The Astrophysical Journal (Letters)*, 398: L85-L88, 1992.
10. Nonlinear Waves and Solitons in Molecular Clouds, F. C. Adams and M. Fatuzzo, *The Astrophysical Journal*, 403: 142-157, 1993.
11. A Detailed Study of Sheared Alfvén Waves and their Possible Application to Gamma-Ray Bursts, M. Fatuzzo and F. Melia, *The Astrophysical Journal*, 407: 680-686, 1993.
12. Understanding Soft Gamma-Ray Repeaters in the Context of the Extragalactic Radio Pulsar Origin of Gamma-Ray Bursts, F. Melia and M. Fatuzzo, *The Astrophysical Journal (Letters)*, 408: L9-L12, 1993.
13. Extension of the Parker Bound on the Flux of Magnetic Monopoles, F. C. Adams, M. Fatuzzo, K. Freese, G. Tarlé, R. Watkins, and M. Turner, *Physical Review Letters*, 70: 2511-2514, 1993.
14. Magnetohydrodynamic Wave Propagation in One-Dimensional Nonhomogeneous, Self-Gravitating Clouds, M. Fatuzzo and F. C. Adams, *The Astrophysical Journal*, 412: 146-159, 1993.
15. Focusing of Alfvénic Wave Power in the Context of Gamma-Ray Burst Emissivity, M. Fatuzzo and F. Melia, *The Astrophysical Journal (Letters)*, 414: L89-L92, 1993.
16. Nonlinear Stationary Waves and Solitary Waves in Self-Gravitating Fluid Systems with Long-range Forces, F. C. Adams, M. Fatuzzo, and R. Watkins, *Physics Letters A*, 182: 282-288, 1993.
17. General Analytic Results for Nonlinear Waves and Solitons in Molecular Clouds, F. C. Adams, M. Fatuzzo, and R. Watkins, *The Astrophysical Journal*, 426: 629-645, 1994.

18. Physics of Magnetospheric Emission in Soft Gamma-Ray Repeaters, F. Melia and M. Fatuzzo, *The Astrophysical Journal*, 438: 904-907, 1995.
19. Wave Motions in Molecular Clouds: Results in Two Dimensions, C. S. Gehman, F. C. Adams, M. Fatuzzo and R. Watkins, *The Astrophysical Journal*, 457: 718-730, 1996.
20. A Theory of the Initial Mass Function for Star Formation in Molecular Clouds, F. C. Adams and M. Fatuzzo, *The Astrophysical Journal*, 464: 256-271, 1996.
21. An In-Depth Study of Magnetospheric Emission in Soft Gamma-Ray Repeaters, M. Fatuzzo and F. Melia, *The Astrophysical Journal*, 464: 316-331, 1996.
22. The Hard X-Ray to Gamma-Ray Spectrum in EGRET AGNs, M. Fatuzzo and F. Melia, *The Astrophysical Journal*, 508: 601-607, 1998.
23. A Model of the EGRET Source at the Galactic Center: Inverse Compton Scattering Within Sgr A East and its Halo, F. Melia, F. Yusef-Zadeh and M. Fatuzzo, *The Astrophysical Journal*, 508: 676-679, 1998.
24. A Self-Consistent Model for the Broad-band Spectrum of Sgr A East at the Galactic Center, F. Melia, M. Fatuzzo, F. Yusef-Zadeh and S. Markoff, *The Astrophysical Journal (Letters)*, 508: L65-L69, 1998.
25. Electron-positron Annihilation Radiation from Sgr A East at the Galactic Center, M. Fatuzzo, F. Melia and J. Rafelski, *The Astrophysical Journal*, 549: 293-302, 2001.
26. Is Thermal Expansion Driving the Initial Gas Ejection in NGC 6251?, F. Melia, S. Liu and M. Fatuzzo, *The Astrophysical Journal*, 567: 811-816, 2002.
27. Enhancement of Ambipolar Diffusion Rates through Field Fluctuations, M. Fatuzzo and F. C. Adams, *The Astrophysical Journal*, 570: 210-221, 2002.
28. Dynamical Stability of Earth-like Planetary Orbits in Binary Systems, E. M. David, E. V. Quintana, M. Fatuzzo and F. C. Adams, *The Publications of the Astronomical Society of the Pacific*, 115: 825-836, 2003.
29. A Kinship between the EGRET Supernova Remnants and Sagittarius A East, M. Fatuzzo and F. Melia, to appear in the October 20 issue of *The Astrophysical Journal*.
30. More Track and Field, M. Fatuzzo and T. Toepker, accepted for publication in *The Physics Teacher*.