Sabbatical Application for the 2016-2017 Academic Year

Name: Paul J. Wiita
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Department of Physics
Proposal Title: **Measuring and Modeling Variability in Quasars and Blazars**
Date: 16 September 2015
Month and year of first appointment at TCNJ: August, 2010
Dates of previous sabbatical leaves: none at TCNJ. Previous leaves from Georgia State University were for: fall 1988 term at the Institute for Theoretical Physics, University of California, Santa Barbara; the 2000-01 AY at Dept. Astrophysical Sciences, Princeton University; the 2008-2009 AY at the School of Natural Sciences, Institute for Advanced Study, Princeton
Current Application is for the Full Academic Year

I have notified by dean and department chair of my intention to apply for a sabbatical leave.

Paul J Wiita ______ Applicant (signature)

Paul J Wiita ______ Chairperson (signature)

______ Dean (signature)

Description: Brighter than a Trillion Suns, Yet Changing in Minutes

Active galaxies are the most powerful objects in the universe, with quasars often shining hundreds of times brighter than all of the 10^{11} to 10^{12} stars in their host galaxies. Quasars, radio galaxies (RGs), Seyfert galaxies, and BL Lacertae objects are all types of active galactic nuclei (AGN), characterized by significant variations as well as great luminosities (Urry & Padovani 1995). Roughly 10% of all AGN are radio-loud, launching oppositely directed jets of plasma (ionized gas) at relativistic speeds (usually >90% of the speed of light) into the interstellar, then intergalactic, gas. Strong shocks form at the ends of the jets, where the relativistic outflows slow down and fill giant lobes with plasma that emits photons through the synchrotron emission mechanism (Rector & De Young 2008). Some of these RGs are the largest physically connected objects in the universe, extending to more than 10^7 light-years (100 times the size of our Milky Way), and these active phases typically last for tens to hundreds of millions of years.

The great powers and the jets are produced in the vicinity of the supermassive black holes (SMBHs, typically between 10^6 and 10^9 solar masses), which are located at the cores of most, if not all, galaxies (Merritt 2013). As matter falling into a SMBH will almost invariably have angular momentum, it will not plunge straight in. Rather, it will spiral in through an accretion disk, in which angular momentum is extracted through (mostly) magnetic viscosity and its gravitational potential energy is eventually converted into heat; much of that is radiated away in visible and ultraviolet photons. Changes in magnetic field topology produce analogs of solar flares in a corona above the accretion disk yielding fluctuating X-ray emission (Wilkins & Gallo 2015). Under appropriate conditions, a fraction of the mass of the accretion disk will be ripped off when organized magnetic fields become strong enough close to the SMBH. Those fields can accelerate and collimate the plasma into two relativistic jets perpendicular to the disk (Stepanovs et al. 2014).

When these relativistic jets point close to our line of sight their emission is “Doppler boosted” and they can appear hundreds, or even thousands, of times brighter than they are in their emitted (“rest”) frames. This critical result from special relativity also means that their variations are observed to occur substantially faster (typically 3-30 times) than they are in their rest frames (Gopal-Krishna et al. 2003). This effect means that a few percent of RGs seem much brighter and vary much faster than others and are thus called “blazars”. Though we now understand a great deal about AGN, many fundamental mysteries remain about the exact composition of the jets, their propagation, stability and internal structures. During my sabbatical I would address some of these questions through additional observations in optical and X-ray bands as well as improved numerical modeling of jet stability and turbulence.

For the past 40 years I have been studying RGs, quasars. blazars, and other AGN. My Ph.D. thesis included the first numerical models of RG jet formation and growth (#4 in my CV, below). Since then my students, colleagues and I have performed increasingly sophisticated theoretical and analytical work on RGs (CV## 3,6,9,10,18,20,29-32,34,35,38,39,42,49,54,60, 61,64, 65,71,76-79, 86,88,91,95,100,104-107,113,115,121,130), and numerical models of RGs (CV## 12,19,25,28,33,40, 52,57,62,68,72,84,96,102,103,122,149). For the past 22 years, an increasing portion of my effort has gone into measurements of variability from various classes of AGN, as a theorist interpreting observations using visible light made by colleagues, often at my instigation (CV## 44,56,59,74,85,90,92,93,97,99,108,116,118,120,124, 126-129,132-136,138-140,144,145, 151,153, 154); more recently these studies have involved X-ray emission too (CV## 112,114,119,147,150).

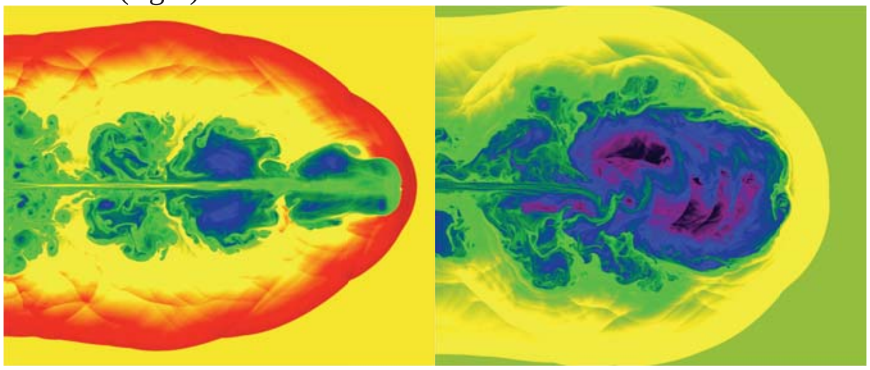
Because of their tremendous distances, no telescope is able to resolve the core regions of

AGN. The best attempts come from Very Long Baseline Interferometry, using radio telescopes separated by thousands of km; combining those measurements can provide angular resolution (though not sensitivity) equivalent to a single telescope of that diameter, corresponding to milli-arcseconds of angle or light-years in size. On the other hand, if something is observed to vary substantially over the course of just minutes (as many AGN do), then, as nothing can move faster than light, the emitting region cannot be more than several light-minutes in size. Actually, taking into account special relativity, it might really be a light-hour in size; nonetheless, temporal changes can provide unique information on the smallest possible scales, corresponding to the inner parts of an accretion disk or small fractions of a jet's diameter.

The chief observational work to be performed during a sabbatical will consist in designing and organizing additional and new campaigns to monitor AGN, particularly blazars, in multiple bands simultaneously. I have been involved in several of these campaigns, most recently for the blazars 3C 273 (#150), BL Lacertae (#154), S5 0716+714 (Preparation #4) and 3C454.3 (Preparation #5). In the foregoing efforts, data from multiple ground-based optical telescopes, several radio telescopes, and X-ray and even gamma-ray telescopes (on satellites) have been combined to obtain a fuller understanding of the regions producing the variability. The next step is to look for slightly fainter AGN for which we can still gather large amounts of high quality data. I will lead this work in collaboration with Dr. Alok Gupta in at the Aryabhatta Research Institute of Observational Sciences, Nainital, India.

Dr. Ann Wehrle and I have a NASA grant for work on the blazars OJ 287 and 3C 446, where we will combine the high precision and nearly continuous optical measurements made with the Kepler satellite with simultaneous gamma-ray measurements being made with the Fermi satellite. We will reduce, process and analyze the observations to provide high quality visible light curves similar to those in our earlier work (##138, 145), that we will correlate with Fermi data to determine if both types of photons are produced from the same region or not. We will search upcoming Kepler observational fields to locate additional AGN that are bright enough to observe and then request time on X-ray satellites as well as organize monitoring with additional ground based optical telescopes. We will then propose for additional NASA support to gather and analyze those data, and plan submission of a multi-year grant proposal to NASA to conduct more sophisticated non-parametric statistical analyses on the entire set of Kepler AGN data.

The theoretical/computational work I will lead involves upgrading the recent models of turbulent jets (#149) and propagating fluctuating jets (Submitted #3) my students here and I have done over the past three years. Currently, we use the Athena code (Beckwith & Stone 2011). Our models are purely hydrodynamical and are computed in 2-dimensions, so we essentially follow a slab of relativistic fluid, rather than a cylindrical jet, propagating through an external medium. By combining models of turbulent flows with the large-scale wiggles of the jet, both of which produce changing Doppler factors, hence variability, we have computed model light curves and their power spectra. For certain parameters, these do a good job of matching those of blazars, all the way from hours to decades. We have considered a wide range of jet velocities, turbulence strengths, and ratios of jet density to external gas density. *No other model has produced such reasonable appearing variations over such a large temporal span.* While 2D models have been shown to provide decent approximations (Koide et al. 1996) and are still very useful, they are not state-of-the-art, but we can do no better using the small computers currently available at TCNJ. Also, the purely hydrodynamic models only allow us to crudely approximate the actual emission (in the rest frames) as computing synchrotron emission requires knowing both magnetic field strengths and directions. Density slices through one stable (left) and one unstable (right) simulation are shown below.



I would use the 3D and magnetohydrodynamic (MHD) features of Athena, which will soon have an even more efficient release (J. Stone, private conversation) to set up 3D calculations involving magnetic fields to model the slower variations. I would also upgrade our turbulence code to full 3D (e.g., Marscher 2014) and extend it to a wider range of turbulent eddies, thereby expanding further the wide range of timescales we cover. Together, these efforts, would yield at least one more (first author) paper and *would enable me to write a major NSF proposal to support the last stage of development and then production runs of these computations.*

Methodology: Multi-band Observing Plus 3-Dimensional Jet Simulations

Deciding which AGNs are the most suitable targets for new multi-wavelength observational experiments will require a substantial literature search. I am of course aware of the well-known blazars that we (and others) have examined in the past, and we will continue to observe some of them. However, considering the large number of new blazars discovered recently (e.g., through the Sloan Digital Sky Survey) requires careful combing through optical, X-ray, and radio catalogs to find a rather small number of good targets that are both bright enough in at least two of those bands, and for which we should be able to get observational time. Optical observations are best arranged at several observatories at different longitudes so that the AGN can be followed for lengthy periods as it rises and sets, and doing so requires a great deal of coordination. X-ray satellite time will be applied for during the optical observations.

Although my publication rate has remained high since coming to TCNJ, the demands of administrative and service work have meant that I have fallen far behind on reading the relevant literature required for this major project. Once I have made a large dent in the required reading, I will visit Dr. Gupta, as well as several of my other current collaborators, Drs. Gopal-Krishna, Mangalam, and Agarwal, in India (Pune, Bangalore and Nainital, respectively). There we will conduct the lengthy discussions needed to formulate detailed plans and talk with their colleagues about the optimal way to proceed. (I will pay for the travel personally and my hosts abroad will provide accommodation at their institutes' guest-houses.) During those visits we should be able to finish working on a couple of ongoing projects but will mostly arrange for observations to be carried out toward the end of the sabbatical period as well as during the ensuing year or more.

We have already developed good techniques for analyzing the incoming Kepler-satellite light curves (##138,145) and we have been awarded data on several dozen new AGN. During the sabbatical I would have the time to do the great majority of the analysis and have the rest set up so that TCNJ students could finish it shortly after I return. I would spend the bulk of the sabbatical in the San Francisco area, so I would be able to visit the Kepler Science Team offices at NASA in Mountain View, CA to get personal assistance with the latest reduction software.

For the numerical simulations I will first learn modern MPI coding so that I can use the

Athena code on clusters of cores instead of single machines. This should not be difficult and Athena scales extremely well (https://trac.princeton.edu/Athena/wiki/AthenaDocsScaling). While visiting Berkeley and Stanford (each of which have experts whom I know) I will have access to large computing clusters to perform test runs. These test runs will provide the material needed to apply for a multi-year NSF grant to continue this research. Thanks to ELF funding, TCNJ will acquire a scientific computing cluster over in the 2015-16 FY and by the time I'd return in F17, we expect this cluster to be fully functional and ready for my group to use.

The 3D, special relativistic, MHD version of Athena will produce superb high resolution jet simulations. I will couple this with a 3D version of our turbulence code, which will be a modest effort, and a new synchrotron emission module I will write, which will be a larger one. Together, they will allow my students and me to produce extremely sophisticated simulations of emission variability from propagating jets. Comparing these with observations, *we will gain critical new insights on the location, composition, and velocity of zones producing blazar variability*.

Schedule

June-Aug: Search literature for next targets. Learn MPI coding and MHD module for Athena.
Aug-Sept: Analyze currently available Kepler data and prepare paper with Wehrle.
Oct-Nov: Visit India: design observing campaigns for winter/spring and finalize two papers on current data (in preparation ##5,6).
Dec-Jan: Begin test runs of Athena on clusters at Berkeley and Stanford. Submit next NASA Kepler proposal.
Feb-Mar: Expand turbulence code to 3D. Begin coding synchrotron emission module.
Apr-May: Combine Athena, turbulence and synchrotron codes to make excellent light curves.
Jun-Aug: Analyze first new blazar data and start paper(s) on these data. Debug codes. Start writing multi-year NSF proposal.
(Sept-Nov): Back on campus: finish writing and submit NSF proposal. Start using TCNJ cluster.

Outcomes and Value

A *minimum* of 4 papers will be written and I will be first author on at least 2 of them. A modest proposal to NASA (one more year; like our current Kepler grant) will be written and submitted. Groundwork necessary for a multi-year NSF proposal will be done and the proposal will be begun. The new campus cluster will be used for cutting-edge work in astrophysics.

As in the past, *students will be involved in this research* when I return, both during the academic year and during the subsequent summers (assuming MUSE and/or the NSF grant proposals are successful). In just over 5 years here I have supervised 24 students in 16 distinct research projects: 9 of them presented at national meetings, and 8 of them are co-authors on 4 papers (3 published and 1 submitted). This research will inform my teaching, from Introduction to Astronomy to upper level Galactic & Extragalactic Astronomy and Astrophysics courses.

Finally: I need a break after 6 years as department chair, during which we have hired 4 tenure-line faculty, 4 visiting FT faculty, and a laboratory manager. I have served as Chair of the Sabbatical Committee (2 yrs) and CFA (currently) and am on the Senate Executive Board. As Physics Chair I have a reduced course load; nonetheless, department needs have required me to play "utility infielder" and be in overload in all but one semester. I have taught 7 different regular (1 CU) courses, from an FSP and introductory physics and astronomy through the 400 level; 7 exceeds the number of new preparations of any other department member in that time span. I also have taught both of our seminars and have supervised research students every term.

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