The Young Stellar Cluster in the Ring Around ρ-Ophiuchi

1. Science Justification

1.1 Scientific Motivation

The interaction of newly formed stars with their parent cloud, particularly in the case of massive stars, can have significant consequences for the subsequent development of the cloud. Hot, massive stars will cause cloud disruption through their ionizing flux as well as through the momentum in their stellar winds. Yet, given the right conditions in the cloud, stellar winds may also cause the collapse of cloud cores and induce further star formation. Whether star formation happens sequentially, prompted by previous bursts of young stars, or whether stars all form in one dynamical time and disperse the cloud is under debate (Elmegreen 2000; Hartmann et al. 2001; Tassis & Mouchschovias 2004).

Located only 125pc (de Geus et al. 1989) from the Sun, the Ophiuchus molecular clouds are among the most conspicuous nearby sites of low- and intermediate-mass star formation (Wilking 1992). The dense core, L1688, harbors a rich cluster of young stellar objects (known as the "ρ Oph"[1] cluster; see Figure 1) at various evolutionary stages and is distinguished by high star-formation efficiency (Wilking & Lada 1983 - hereafter WL83).

The stellar content of the L1688 cluster has also been observed at wavelengths ranging between the X-ray and the radio band (Montmerle et al. 1983, Casanova et al. 1995, Barsony et al. 1997, Leous et al. 1991). In particular, the Spitzer observations (a GTO program and the c2d Legacy program) reveal more protostar candidates, most likely embedded in dense gas.

The star ρ Ophiuchi, however, is located one degree to the north and is NOT a member of the "ρ Oph" cluster. ***Much less is known about the gas and stars around the star ρ–Oph.*** In the next sections, we will discuss why the region around the star ρ–Oph is important for understanding the star formation history of the whole ρ Oph region.

1.2 The ρ–Ophiuchus Ring

As part of the COMPLETE[2] Survey of nearby star forming regions, we have recently constructed new temperature and thermal-emission (column density) maps of the Ophiuchus region from IRAS Sky Survey Atlas (ISSA) 60 and 100 μm images (Schnee et al. 2005). We find a ring of warm (37K) dust located approximately 1° to the north of the ρ Oph star-forming region (Figure 1).

Comparison with the extinction map from 2MASS (Alves et al. 2005 as part of COMPLETE) shows that the ***ρ-Ophiuchus ring*** sits inside a "nook" of high-extinction (i.e. cold dense material) on the northern edge of "ρ-Oph" clouds. In fact, this ring was reported by Bernard et al. (1993) in a discussion of the far-infrared emission from Ophiuchus and Chamaeleon, but they did not investigate its nature or possible progenitor. The ring is roughly centered on the young BIV star, ρ Oph, which also powers an oft-photographed bright nebula. The SHASSA[3] H-α image shows a circular nebulosity, indicating the existence of a possible HII region, most likely from ρ–Oph itself. The [SII] emission also shows a bubble coincident with the Hα. A preliminary look at the ratio between Hα and [SII] intensities suggests the existence of a shock front, which is consistent with absorption line studies of CH and CH^+ toward the star ρ Ophiuchi (de Geus 1992).

The presence of a probable HII region suggests that the star ρ–Oph is probably still relatively young, and it would therefore be located near to its birthplace and, assuming a Salpeter-like IMF, within a cluster of several hundred low or intermediate mass stars. If this is the case, then this cluster would comprise a

[1] In this proposal, we refer to the your star cluster in L1688 with quote marks or just simply L1688 cluster to avoid the confusion with the *star* ρ–Oph (center of the dust temperature ring), which is 1 degree to the north the ρ–Oph clouds.

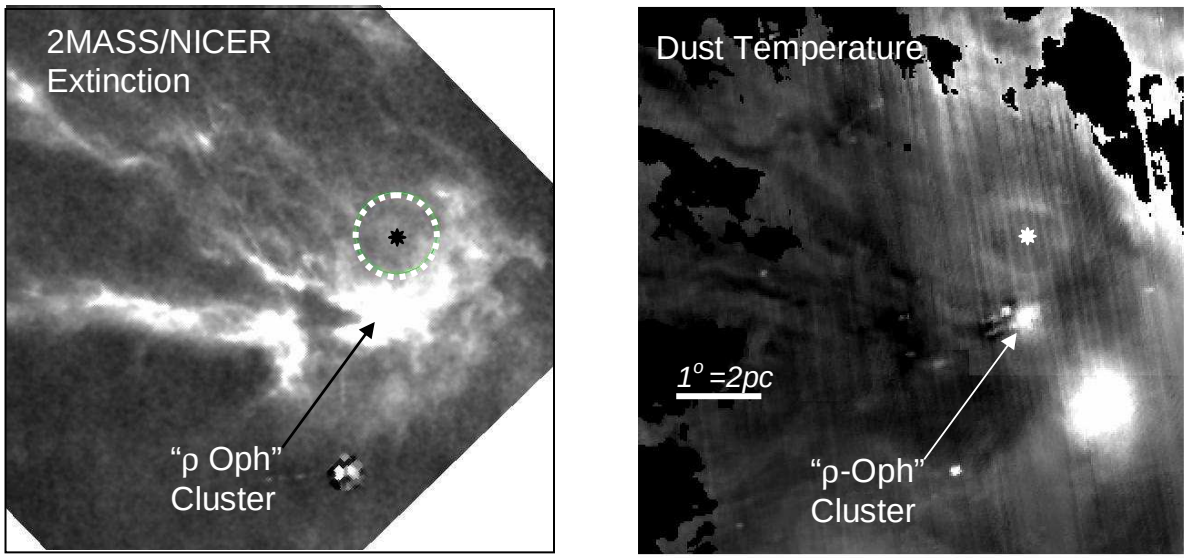
[2] **C**o**O**rdinated **M**olecular **P**robe **L**ine, **E**xtinction and **T**hermal **E**mission; http://cfa-www.harvard.edu/COMPLETE

[3] Southern H-alpha All Sky Survey Atlas; http://amundsen.swarthmore.edu/SHASSA/

significant fraction of the total young stars in the region, and its existence would provide strong evidence for an earlier epoch of star formation in Ophiuchus, which has impact on the dense clouds to its south

There are limited, but very suggestive observations of the young stellar content in the ring. A region around ρ–Oph was serendipitously included in a ROSAT pointed observation made by Snowden et al. in 1994. The data from the pointed observation show about 15 ROSAT-detected point sources within the IRAS ring, all with heavily "reddened" hardness ratios, suggesting that the sources form a loose embedded cluster associated with ρ-Oph.

In summary, the ρ Ophiuchus ring poses interesting questions regarding its origin, its impact, and its young stellar content. There is limited evidence for a young stellar cluster including the massive star ρ Ophiuchi. Combined with our knowledge of the ρ–Oph clouds and its embedded L1688 cluster, this region could become an ideal lab for studying sequential star formation due to its near distance, existence of massive stars, and wealth of multi-wavelength observations available.



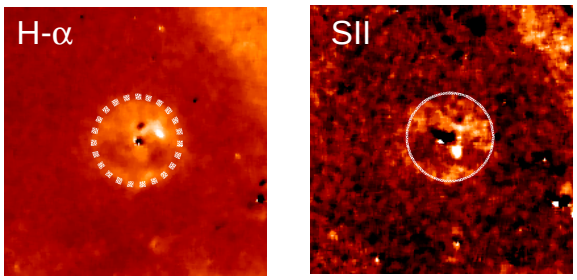


Figure 1: The two upper panels, taken from the COMPLETE Survey, show extinction based on 2MASS data and dust temperature based on IRAS 60 and 100 μm flux. The star symbol in both panels shows the position of the B-star ρ-Oph. The prominent warm ring around this "starred" position is also associated with shell-like ionized gas emission, shown in the panels at bottom right (SHASSA data, courtesy J. Gaustad). The cluster *known as* "ρ-Oph" is actually 1 degree (2 pc) to the *South* of the star ρ-Oph.

1.3 The Advantage of Spitzer over Other Wavebands and Ground Based IR Instruments

There is filamentary dust (and gas) with modest extinction in the ring region. The scattering and reflection of UV and optical light from the young B-IV star ρ-Oph form a bright nebula (Figure 2), which renders the search for point sources in those wavebands difficult. For example, the previous H-alpha emission line survey by Wilking et al. (1987) only detects a few sources in the ring. The X-ray observations to date are not of adequate sensitivity to find all the young stars. ROSAT sources close to the edge of the pointed field are distorted, making it difficult to identify point sources and find counterparts.

The near-IR (e.g. 2MASS) alone is not good at picking out disks, since stellar photosphere emission dominates bands short of K (Gutermuth et al. 2004). The IRAC bands are also less extincted than near-IR bands.

Spitzer would provide crucial information, currently missing, on the nature of the young cluster in the ring. Its sensitivity allows detection of young stars in the Mid-IR bands down to hydrogen burning limit. In terms of bolometric limit, IRAC scans proposed here will achieve 0.5×10^{-3} $L_\odot$ point source sensitivity at the distance of ρ-Oph! Spitzer observations will be able to detect mid-IR emission from disks on the order of earth mass. The closeness of ρ-Oph and the resolution of Spitzer will allow detection of most young stars in the ring region without source confusion. Spitzer observations will likely confirm the existence of a young stellar cluster and provide concrete information regarding its member distribution.

The mid-IR bands of IRAC are excellent for classification of young stellar objects and studying emission from circumstellar disks. The 3 to 8 micron IRAC bands contain little photosphere emission, which makes them sensitive to IR excess emission from circumstellar disks. In particular, the ([3.6]-[4.5], [5.8]-[8.0]) color has been shown (Allen et al. 2004; Megeath et al. 2004) to differentiate well between Class I (protostars with infalling envelopes), Class II (with disks), Class III (pre-main-sequence stars without disks) sources. Allen et al. (2004) has also shown that the reddening in terms of [3.6]-[4.5] is primarily determined by the mass accretion rate of the disk in Class II sources, which makes it a potentially useful disk diagnostic.

1.4 What Can Spitzer Tell Us About the Age of the ρ Ophiuchus Ring Cluster?

Sptizer would provide a complete census of the cluster members, their spatial distribution, and their infrared colors.

In the dense Ophiuchus cloud L1688, IRAC has detected more Class II sources (>50) than Class I sources (~20). Further more, Class I sources are more concentrated toward the dense gas ridge traced by $C^{18}O$, while Class II sources appear beyond the $C^{18}O$ boundaries and are more or less evenly distributed. The number ratio of different class sources and their spatial distribution are important diagnostics of the duration of evolutionary stages of young stellar clusters. The number ratio tells us the relative time of each phase through which the cluster has evolved. The distribution is a combined result of the cluster age and stellar proper motion. The Class I phase of the embedded L1688 cluster has been estimated to be about half a million years (Wilking et al. 1989) based on the roughly equal number of Class I and II sources and the average age of T Tauri stars known at that time. Recently, Wilking et al. (2005) have identified a much older (2-5 Myr) surface population in L1688 using optical spectroscopy. This new result combined with the Spitzer results showing a Class [I/II] number ratio much smaller than 1, means that the age of the L1688 cluster is likely to be older than previously thought.

Using similar method, we will obtain valuable information about the cluster in the ρ Ophiuchus ring. Although there are a small number of Class I sources detected in the L1688 region beyond the dense gas boundary (Allen et al. 2005), very few Class I sources are expected in the ring as this region seems to be partially cleared of dust and gas. We expect to detect a large number of Class II and Class III sources, thus confirming a pre-main-sequence cluster which is *older than the L1688 cluster*. (Some background stars would occupy the same region in the color-color diagram as that of the Class III, which can be somewhat differentiated by cross referencing proper motion catalogues from Tyco2 and UKIRT.) The ratio of Class II to Class III will be a diagnostic of the *evolutionary time of the Class II stage and the ring Cluster*.

We will also examine the possible impact on nearby star formation caused by massive stars through correlation studies. Very close to a massive star (distance < ~0.03pc), the radiation pressure could be important in disturbing disks. Farther away, ionization radiation would drive thermal disk wind thus cause photoevaporation (Shu et al. 1993; Johnstone et al. 1998). These mechanisms of disk dispersion are obviously correlated to the distance to central source and the distribution of ionizing radiation field. We will study the spatial distribution of the mid IR excess emission strength and disk properties (e.g. the accretion rate probed by [3.6]-[4.5] reddening). If the disk emission is correlated with the UV field and statistically weaker toward the ring center, then this is likely caused by radiation from B star ρ Ophiuchi.

The significance of characterizing the ring cluster and discovering the possible impact from massive stars lies in the fact that ρ Ophiuchus is part of the Sco-Cen HI super bubble believed to be blown up by a supernova ~5 Myr ago (de Geus 1992). If our proposed Spitzer observations indeed reveal an older epoch of star formation, this will be a clear example of sequential star formation within the local ρ Oph region. If no such population is to be found, on the other hand, this suggests a single epoch of star formation and gas dispersal.

1.5 Complementary Data and Some Technical Issues

We have been obtaining data covering the ring region for molecular gas (^{12}CO, ^{13}CO), atomic gas (HI), and dust (800 μm; Johnstone et al. 2004). The kinematic information from molecular and atomic spectroscopy will provide us estimates of the dynamic time scale of the ring structure in the ISM. This time scale can be checked with the evolutionary time scale of the young stellar cluster inside.

We have had extinction map derived from 2MASS (Figure 1), which provides large scale dust structure and reddening information. The extinction, combined with gas surface temperature from ^{12}CO can be used to study the distribution of UV field strength (Li et al. 2003). The UV field strength will be correlated with disk properties as described in the section above.

We expect some contamination from the background galaxies in the point sources (especially Class II and III) identified by IRAC. We will cross reference these sources with the proper motion available from existing catalogue (e.g. Tyco 2) to help confirm cluster member association.

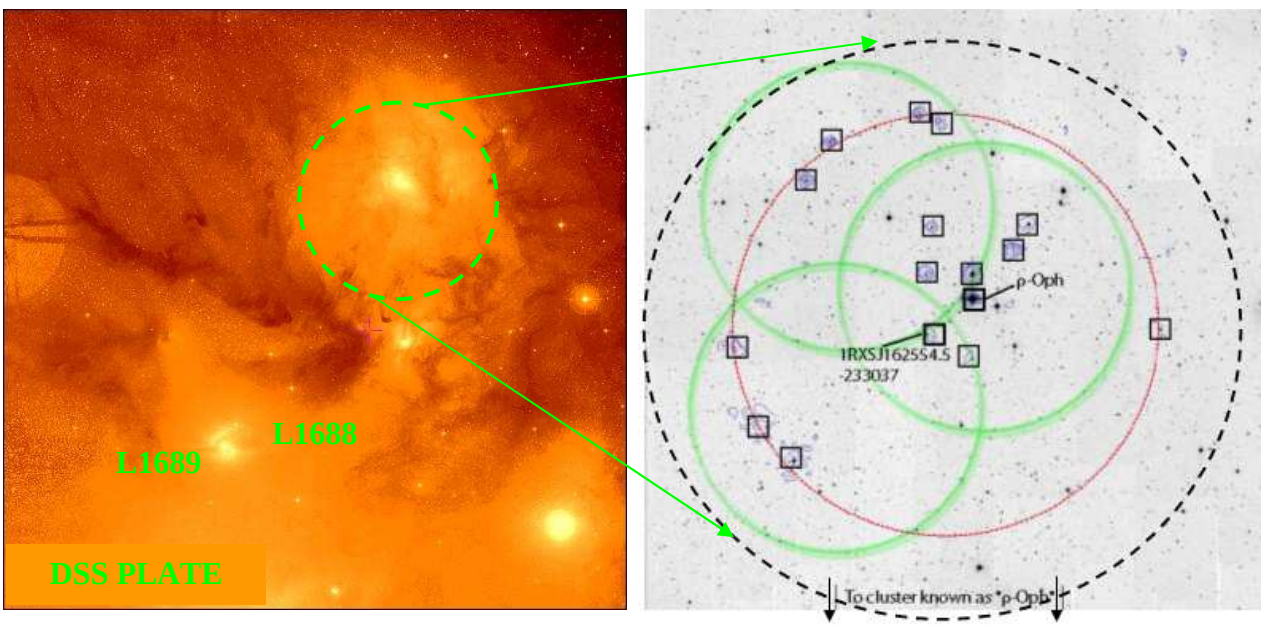
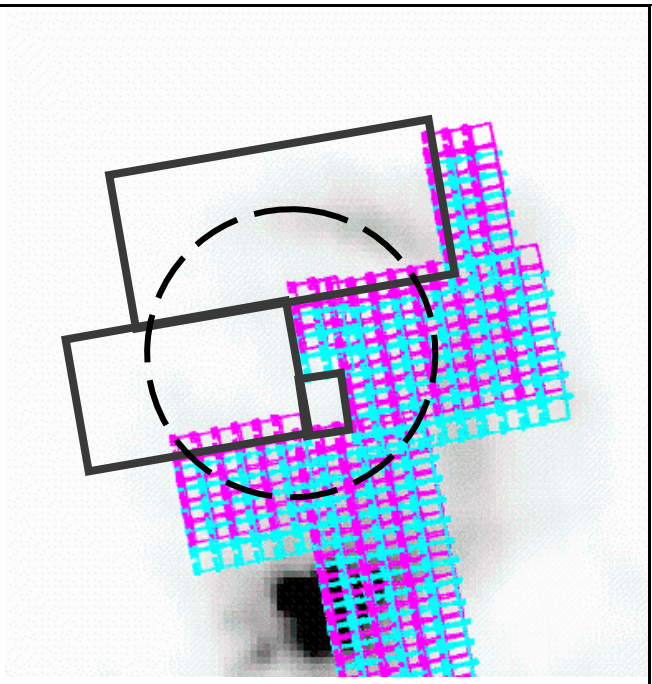


Figure 2: Left: Digital Sky Survey image. Right: 2MASS image overlaid with ROSAT contours of 0.3, 0.5, 1.0, 1.5, and 3.0 counts/arcsec. The dashed circle (in both panels) is 1° across and shows the location of the r-Ophiuchi ring. The smaller squares are possible ROSAT sources, some of which seems to lie on a smaller circle (red). The three overlapping green circles and the red circle are visual aids for the location of the X-ray sources.

2. Technical Plan

We plan to use IRAC in HDR mapping mode. Three maps are needed to completely cover the ρ-Oph dust ring without unnecessary repetition of the area already included in the c2d legacy program. For the best mosaicing product, these three maps (6 AORs) are to be done within 30 days to avoid significant rotation of the array.

Figure 3 illustrates the principle layout of our mapping strategies.



Each cloud map employs two dithers. Each map is repeated four times to build effective integration to 96 seconds. This integration is needed to achieve the photometric accuracy needed for measuring good mid-IR colors and reddening (especially [3.6]-[4.8]). For example, the spread caused by mass accretion rate in [3.6]-[4.8] is about 0.6 mag and our proposed observations would achieve an error bar (3 σ) of about 0.1 mag.

Such multiple coverage separated by no more than 30 day also help to ensure credible detection of bright sources, considering the high probabilities of fast moving targets (e.g. asteroids) in this area of the sky.

The scan spacing is chosen to match that of the AORs from the c2d Legacy program to facilitate eventual combination of both data sets to produce images of the full ring.

In the ρ-Oph region, the 8 micron band has by far the strongest background radiation, at about 21 MJy/Sr. This is still way below the saturation limit for our short exposures. The expected sensitivity for extended sources is around 0.03 MJy/Sr at 3.6 and 4.8 micron bands and around 0.14 MJy/Sr at 5.8 and 8.0 micron bands. In terms of bolometric limit, IRAC scans will achieve 0.5×10^{-3} solar luminosities (point source) at the distance of ρ-Oph.

Figure 3 The IRAC coverage of the c2d program is shown in grids based on output from the SPOT program. Only those adjacent to the proposed observations are shown. The black rectangles illustrate our proposed IRAC maps. The dashed circle shows the approximate location of the ρ-Oph dust ring.

3. References

Allen et al. 2004, ApJS, 154, 363
Allen et al. 2005, in prep
Alves et al. 2005, in prep
Barsony et al. 1997, ApJS, 112, 109
Bernard et al. 1993, A&A, 277, 609
Casanova et al. 1995, ApJ, 439, 752
Elmegreen 2000, ApJ, 530, 277
Gutermuth et al. 2004, ApJS, 154, 374
Hartmann et al. 2001, ApJ, 562, 852
de Geus et al. 1989, A&A, 216, 44
de Geus 1992, A&A, 262, 258
Grosso et al. 2000, A&A, 359, 113
Imanishi et al. 2001, ApJ, 557, 747
Johnstone et al. 1998, ApJ, 499, 758
Johnstone et al. 2004, ApJ, 611,45L
Leous et al. 1991, ApJ, 379, 683
Loren 1989, ApJ, 338, 902
Megeath et al. 2004, ApJS, 154, 367
Montmerle et al. 1983, ApJ, 269, 182
Motte et al. 1998, A&A, 336, 150
Shu et al. 1993, Icarus, 106, 92
Schnee et al. 2005, in prep
Snowden et al. 1994, AAS, 184, 4813
Tassis & Mouchschovias 2004, ApJ, 616, 283
Wilking 1992 in ESO Sci. Rep. No. 11, ed. B. Reipurth
Wilking & Lada 1983, ApJ, 274, 698
Wilking et al. 2005, in prep

4. Brief Resume/Bibliography

Di Li

- **Education**

PhD in Astronomy, Cornell University 2002, Master in Astronomy, Cornell University, Bachelor of Science in Nuclear Physics, Beijing University 1995

- **Current Employment**

Astronomer, Havarvd-Smithsonian Center for Astrophysics

- **Professional Experience**

Planning and observing: SWAS satellite, CSO, SEST, FCRAO, Effelsberg, GBT, VLA, Arecibo

Data reduction: SWAS pipeline, Arecibo Class Calibration Software

Modeling: Dust modeling, Monte Carlo radiative transfer

- **Grant and Award**

GBT Grant, *National Radio Observatory*, 2004

Small Research Grant, *American Astronomical Society*, 2002

First Class Fellowship, by *Beijing University*, 1992

GuangHua Scholarship, by *GuangHua Foundation*, 1992

- **Society Membership**

AAS, APS, CAS

- **Research Interest**

Modeling dust mass distribution in interstellar medium through the inversion of dust IR emission spectrum. Constrain the initial conditions of massive star formation through multi-wavelength mapping starless cores in Orion. Using HI narrow line self-absorption to characterize of age of molecular clouds and measure magnetic field inside dense clouds. Surveying the gas content (both atomic and molecular) of the Ophiuchus region to characterize the chemical and physical conditions of a medium mass star formation.

I am the PI of a large scale mapping project using SWAS and FCARO to study carbon and gas dynamic in the Ophiuchi region. I am the PI of two GBT programs and several Arecibo program to study atomic gas in star forming clouds. I am a CoI in two survey projects, the COMPLETE, which covers three nearby star forming regions included in the Spitzer Legacy program "From Molecular cores to Disks" and the ALPHA-TAU, covering Taurus. Both projects seek to build multi-wavelength data base to study the evolution of ISM and the formation of stars.

Relavant Publications

Allen et al. 2004, *Infrared Array Camera (IRAC) Colors of Young Stellar Objects*

Goldsmith, P. F., Li, D., Melnick, G. J., Bergin, E. A., Howe, J. E., Snell, R. L., Neufeld, D. A. & Harwit, M., 2002, *Tentative Detection of Molecular Oxygen in the Rho Ophiuchi Cloud,* ApJ, 576, 814

Goldsmith, P.F & Li, D. 2004, *HI Narrow Self--Absorption in Dark Clouds: Correlations with Molecular Gas and Implications for Cloud Evolution and Star Formation,* Accepted by ApJ

Goodman A.A. et al. 2004, *The COMPLETE Survey of Star-Forming Regions at Age 2,* to appear in the Proceedings of the 60th Birthday Celebration for F. Shu, D. Hollenbach & C.McKee.

Li D., Goldsmith, P.F. & Menten, K. 2003, *Massive Quiescent Cores in Orion I. Temperature Structure,* ApJ, 587, 262

Li, D., 2002, *CO and CI Surveys of the Ophiuchi Region,* in SF Chem 2002, ed. C. Curry and M. Fich

Ridge, N.A., Wilson, T.L., Megeath, S.T., Allen, L.E. & Myers, P.C. 2003, AJ, *A ^{13}CO and C^{18}O Survey of the Molecular Gas Around Young Stellar Clusters within 1 Kiloparsec of the Sun*, 126, 286

Zubko, V., Li, D, Harwit, M & Lim, T. 2004, *Observations of Water Vapor Outflow from NML Cygnus,* ApJ, 610, 42

Data Analysis Funding Distribution

PI	D. Li	70%
Co-I	L. Allen	30%

Status of Existing Observatory Programs

The PI has no existing Spitzer program in which he is the contact person.

Financial Contact Information

John G. Harris
Contracts, Grants, and Property Management Department
Mail Stop 23, Smithsonian Astrophysical Observatory
60 Garden Street, Cambridge MA 02138
Phone: 617-495-7446 **Email**: jharris@cfa.harvard.edu