Low-Luminosity, Compact Accretion Sources in the Galaxy

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Accretion onto compact stellar objects (white dwarfs, neutron stars, and black holes) from companions in close binaries is the primary beacon for study of the astrophysics of the extreme: from endpoints of stellar and binary evolution, to the physical processes in the extremes of gravity, radiation, or magnetic fields. Accretion from the interstellar medium on the presumed still larger population of isolated compact objects should, at least for relatively more massive and low-velocity stellar black holes, also be observable in certain conditions, yet never has been. Given the fundamental role that accretion plays in so many key problems of interest in current astrophysics, it is surprising that the space density and luminosity function(s) of the most common accretion-powered compact objects—white dwarfs accreting from low-mass stellar companions, or cataclysmic variables (CVs)—has not been measured to better than a factor of ~10 in the solar neighborhood, and they have even less well-known spatial distributions in the Galaxy.

Motivated by these and related questions, we set out in 2000–2001 to conduct a survey of low-luminosity accretion sources in the Galaxy with the newly-launched Chandra X-ray Observatory. We proposed the Chandra Multiwavelength Plane (ChaMPlane) Survey to constrain

- CV space density and X-ray luminosity functions (XLFs) in the disk vs. Bulge;
- Galactic Bulge source populations;
- Populations of quiescent low-mass X-ray binaries (qLMXBs) with neutron star and black hole primaries and isolated BHs;
- Be-High Mass X-ray binaries (HMXBs);
- Stellar coronal XLFs in the disk vs. Bulge.

Chandra would first detect low-luminosity (e.g., $L_x \sim 10^{31}$ erg/s at ~8kpc) sources with sufficient precision ($\leq 1$ arcsec) to enable their optical counterpart candidates to be selected and then identified with follow-up spectroscopy for final classification and study. Optical identifications were essential, so we also proposed a five-year NOAO Survey Program to do deep imaging ($R \sim 24.5$) with the Mosaic I and Mosaic II CCD cameras on the Kitt Peak and Cerro Tololo 4-m telescopes. To detect the faintest accretion source candidates by their (near) ubiquitous Hα emission, as well as to prioritize spectroscopy, the Mosaic imaging is comparably deep in Hα and R to derive (Hα−R) colors; exposures in V and I allow color-color classification.

The survey was conceived as a serendipitous source survey using primarily archival Chandra data that would be reprocessed with a uniform set of custom tools to ensure careful treatment of astrometry for optical identifications, and derived source fluxes for a range of model spectra and absorption columns for both the source number-flux distribution, logN-logS, and X-ray spectral classification.

Initial ChaMPlane results were given for logN-logS in several Galactic fields (Grindlay et al. 2003, AN, 324, 57), as well as an early description of the Mosaic imaging identification survey (Zhao et al. 2003, AN, 324, 176). The survey has now achieved nearly its original goal of ~100 Chandra ACIS-I or ACIS-S galactic plane fields, with in fact 94 now selected (through Chandra cycle 6). These have $|b| \leq 12^\circ$, exposure times ≥12 ksec (most are >20–30 ksec), and are selected to avoid dense clusters or bright diffuse optical emission, and (if possible) to have a minimum hydrogen column density in order to maximize the detection and subsequent identification of faint point sources. These 94 ACIS fields are covered by 59 Mosaic fields (36 x 36 arcmin), as shown in figure 1.

In figure 2, we show a “typical” resulting color magnitude diagram and color-color diagram for a 16 x 16-arcmin field corresponding to one of the 30 short (12 ksec) Chandra ACIS-I exposures in the Galactic Center Survey (Wang et al. 2002, Nature, 415, 148), which contained 46 sources. All of this 2″ × 1′ survey centered on SgrA* was covered in five of our deep Mosaic images. One bright Hα object is detected out of the ~12,000 stars with >5σ detections in R and Hα (vs. ~23,000 in R alone), although many others are below the nominal threshold of (Hα − R) < -0.3 and are primarily dMe stars. However, our follow-up spectra in June 2004 with the Blanco 4-m and Hydra (see figure 3) showed the bright-emission (R = 18.7) object to be a CV. The small displacement off the main sequence track in the color-color diagram suggests it has a small extinction ($A_v \sim 1$). Using the distance versus...
A model of Drimmel et al. (2003, ApJ, 409, 205) gives a distance of ~1.2 kpc, and thus $M_v = 8.0$, consistent with a K7 secondary and its de-reddened colors. The Chandra flux in the 2-8 keV band is $1.0 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, which when de-reddened by $A_V$ gives log($F_{\text{X}}/F_{\text{X}}$)$_{\text{reddened}}$ = +0.9 and luminosity $L_X = 3.7 \times 10^{31}$ erg s$^{-1}$, both of which are typical values for a CV.

Full results on this object, as well as other tantalizing results in the Bulge, are in preparation or have been submitted (e.g., our results from IR (JHKBrγ) imaging of a 10-arcmin field around SgrA* with Magellan/PANIC, which rules out Be-HMXBs for the SgrA* cusp sources; see Laycock et al. 2005). We have submitted three papers to the Astrophysical Journal describing the overview of ChaMPlane and initial constraints on the CV population from 14 fields in the Galactic Anticenter (Grindlay et al. 2005), a description of the X-ray processing and X-ray results for these Anticenter fields (Hong et al. 2005), and a detailed discussion of the optical/Mosaic survey processing and example results for one of the Anticenter fields (Zhao et al. 2005).

The deep Mosaic images of now ~21 square degrees of the Plane and photometric catalogs are being archived on the ChaMPlane Web site (hea-www.harvard.edu/ChaMPlane) as regions are submitted for publication. The first 14 Anticenter fields are on line, together with Web-based tools for their analysis and display. Many other projects could be conducted with these deep Hα images and photometric catalogs. We are extremely grateful for the NOAO Survey Program having made this possible.
Gemini Observations of the Two Intrinsically Brightest Minor Planets

Chadwick Trujillo (Gemini Observatory), Michael Brown (Caltech), David Rabinowitz (Yale University) & Thomas Geballe (Gemini Observatory)

We have obtained first-look observations of Orcus and Sedna (provisional designations 2004 DW and 2003 VB12) in order to place constraints on their composition. These two planetary objects are unique in that they have the largest absolute magnitudes of any minor planets (this includes all asteroids, comets and Kuiper Belt objects, but not moons or planets). Orcus and Sedna were both discovered within the past two years as part of our ongoing survey of the outer solar system. Although they are brighter in an absolute sense when compared to all other minor planets, they are quite faint due to their extreme distance. Orcus is farther from the Sun than Pluto and is likely to be at least 1/3 the size of Pluto if its albedo is similar to that of other icy planets, which have albedos around 30%. Sedna is 60% farther from the Sun than any other known body bound to the solar system and is probably similar in size. The most interesting aspect of Sedna is its orbit: its perihelion of roughly 70 AU is 60% farther than any other solar system body.

The extreme distance of Sedna (reaching about 1,000 AU at aphelion) means that surface temperatures from solar heating never exceed 38 Kelvin (dropping to 11 Kelvin at aphelion). We do not know what to expect on such an extreme surface, because no solar system surfaces with such peculiar orbits have been studied. However, two possibilities present themselves: (1) the surface could be rich in volatile ices, which could be present based on the low temperature of the body as is the case for Pluto and Pluto’s moon Charon; or (2) the surface could be devoid of any ices, as bombardment by cosmic rays and solar UV should carbonize simple

Spectrum of Orcus. At the top of the plot, the relative reflectance spectrum of Orcus (black filled circles) is compared with the best-fit water ice model (black line) and 1-sigma limits on the best-fit model (gray lines). For comparison, the spectrum of the nearby sky (gray circles) is shown at the bottom of the plot. The middle spectrum shows the residual model of Orcus after subtracting the best-fit water ice model (hollow circles, offset vertically for clarity). The gray line on the middle spectrum illustrates the 3-sigma methane ice model. Any greater amount of methane is ruled out by our observations. The model shown is for 100-µm diameter particles. Spectrum error bars are computed from the reproducibility of the spectral data in each spectral point.

continued
ices on megayear timescales if there is no other resurfacing process.

The near-IR is the preferred wavelength regime to study icy planetary surfaces. Ices such as water, methane, methanol, ammonia, carbon monoxide, and nitrogen all have broad absorptions in the K-band in particular. Using Gemini North’s Near Infrared Imager (NIRI), we collected about two hours of on-source K-band spectroscopy from each of the targets within a few months of their discovery. This was enough to place crude limits on basic surface composition (with more detailed studies to follow).

Sedna’s spectrum appears featureless in the data collected. However, the signal-to-noise ratio was high enough to rule out strong ice absorptions, such as those found on Pluto (whose spectrum is dominated by methane ice) and Charon (whose spectrum is dominated by water ice). Orcus, on the other hand, shows strong signatures of water ice (see the figure). This is not unexpected, since several other Kuiper Belt objects (KBOs) have been shown to have water ice. We hope that deeper studies of these two objects will reveal additional ice species.

Using the data already in hand, we can place some crude limits on the surface properties of Sedna and Orcus. Our conclusions are limited primarily because the albedos of Sedna and Orcus are unknown. Using Hapke modeling of the collected spectra, we find to 3-sigma confidence that the surface of Sedna must be covered by less than 70% water ice under most grain models and albedo combinations studied. Assuming moderate to large grain models (diameters 100 µm or larger), the surface of Sedna must be covered by less than 60% methane ice, to 3-sigma confidence. For Orcus, the best-fit models for grain diameters 25 µm and larger suggest that the water ice surface fraction is less than 50%. Additionally, unless grain diameters on Orcus are smaller than 25 µm, its surface cannot be covered by more than 30% methane ice. When the albedos of Sedna and Orcus are measured, the above results will be significantly more constrained, as only one albedo model need be considered.

These numbers aside, it is clear that the surface of Sedna is very unlike that of Pluto or Charon. Instead, it is consistent with a surface processed by cosmic rays and solar UV radiation. Orcus, on the other hand, is more typical of some KBOs, with up to 50% water ice, and so far, no other identified species. We are anxious to see what deeper spectra will reveal about these two most extreme minor planets.

This work will be published this summer in the Astrophysical Journal (available on line at xxx.lanl.gov/abs/astro-ph/0504280).
The Sun’s New Neighbors

Todd Henry (Georgia State University)

The Cerro Tololo Inter-American Observatory Parallax Investigation (CTIOPI) began in August 1999 under the auspices of the NOAO Survey Program as a significant research track of the Research Consortium on Nearby Stars (RECONS). Since February 2003, CTIOPI has been continued as part of the Small and Moderate Aperture Research Telescope System (SMARTS) Consortium. CTIOPI is an international collaboration with the primary goal of revealing unrecognized neighbors of the Sun. Particular emphasis is placed on red dwarfs within 10 pc (the horizon of the RECONS sample) and white dwarfs within 25 pc. The latter distance is the horizon of the Nearby Stars Project (NSars) and Catalog of Nearby Stars (CNS) programs, which are US and German efforts to provide compendia of stars within 25 pc.

Three groups in the United States (Todd Henry, Wei-Chun Jao, and John Subasavage at Georgia State University; Phil Ianna and Jennifer Bartlett at the Small and Moderate Aperture Research Telescope System (SMARTS) Consortium. CTIOPI was carried out on the CTIO 0.9-m and 1.5-m telescopes through time granted by NOAO, and the program continued on the 0.9-m as part of SMARTS. The first results from both programs have recently been published (Jao et al. 2005, AJ, 129, 1954, for the 0.9-m program) or are in press (Costa et al 2005, AJ, July issue, for the 1.5-m program). We observe promising nearby star candidates that have some combination of high proper motions, photometric, or spectroscopic information indicating a small distance from Earth. A trigonometric parallax series is typically considered finished when we have acquired at least 40 frames over a two-year period, yielding parallax errors of ~2 mas.

From the 0.9-m program, we have determined 217 parallaxes to date—20 are for new systems in the RECONS 10-pc sample, and an additional half dozen have been placed firmly within 10 pc for the first time (previous parallaxes had large errors). We have also found 110 more systems between 10 and 25 pc. For comparison, only 195 trigonometric parallaxes from ground-based efforts have been published since the definitive Yale Parallax Catalog (van Altena et al. 1995). Perhaps most importantly, the new 10 pc members constitute a 10% increase in the RECONS sample, illustrating that we have many neighbors with whom we are not familiar. In the table, we present a few of the more intriguing distance determinations. This list is not exhaustive, and these results should be considered preliminary. Definitive results are forthcoming in the Astronomical Journal as part of the RECONS series of papers entitled “The Solar Neighborhood.” What becomes clearer with each round of parallax reductions is that the Universe is dominated by the Sun’s small red dwarf cousins, which account for more than 70% of all stars.

During complementary photometric programs on the 0.9-m, we have also amassed VRI photometry for more than 400 systems. Spectral typing work carried out on the CTIO 1.5-m during SMARTS time has also allowed us to determine definitive spectral types for more than 500 systems. This allows us to evaluate the true natures of the stars we place on the CTIOPI observing list for intense observations. When combined, these astrometric, photometric, and spectroscopic efforts provide a complete portrait of our stellar neighbors. They also provide an ideal research environment in which young astronomers can learn many tools of the trade.

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Magnetic Field Changes during Solar Flares

Jeff Sudol & Jack Harvey (NSO)

Solar flares have been an astrophysical mystery for almost 150 years. Observations have shown that these explosions, the largest in the solar system, occur in the solar atmosphere above strong, complicated, and presumably stressed magnetic field configurations. Estimates of the energy required to power solar flares, together with their association with complicated magnetic fields, led to the conclusion that flares must be electromagnetic in origin.

In the 1950s it became possible to map the magnetic field in the photosphere and the search for magnetic field changes during solar flares ensued. From the 1950s through the 1990s, positive and negative reports of magnetic field changes appeared in the literature, leaving the situation confused. Transient magnetic field changes were often reported, but these proved to be an instrumental effect, the result of line profile changes caused by the heating of the plasma along magnetic field lines. In the past six years, however, high-quality, high-cadence observations have provided unequivocal evidence of abrupt and permanent changes in both the longitudinal and transverse magnetic field during solar flares.

Most publications have presented results for a single event. Magnetograms from the global network of GONG telescopes have afforded us a unique opportunity to assess the characteristics of magnetic field changes during solar flares for a large number of events. The GONG magnetograms, which show the line-of-sight component of the vector field across the entire solar disk, are available at a one-minute cadence. The magnetograms have a spatial resolution of 5 arcsec and an instrumental noise of about 3 G.

To characterize the magnetic field changes during solar flares, 15 X-class flares were selected for which continuous magnetograms from a single GONG site were available for at least one hour before and after the peak of the flare. Each image was remapped to an overhead view with compensation for solar rotation (see figure 1). Previous work, including observations in November 2000 with the GONG+ prototype, showed that the magnetic field changes are quite abrupt and can be modeled with a simple step function. A model of the magnetic field as a function of time, allowing for the evolution of the field and an abrupt change in the field, was fit to each pixel. Maps of the fit parameters were constructed to show the characteristics of the field changes across the active region. Based on these parameter maps, 42 sites were identified where a significant change in the magnetic field had occurred. For each site, a representative point, the point where the most abrupt and the strongest change in the field occurred, was selected for further study.

We have found that abrupt, significant, and permanent field changes occurred in at least one location in the flaring active region during all 15 flares. The magnitudes of the field changes range from 30 G (the detection limit) to almost 300 G. In 70% of the cases, the magnetic field change occurred on a time scale

Figure 1. (a) A remapped GONG “white light” image of the flaring active region on 2 November 2003. The image is 128 pixels square. The image scale is 0.125° per pixel in heliographic coordinates. (b) A remapped GONG magnetogram of the same active region. Black indicates negative field; white indicates positive field. (c) A map of the fit parameter for the change in the magnetic field. Black indicates a decrease in the field, white indicates an increase. The black and white boxes in each image denote the positions of the representative points used in our analysis. (d) A plot of the longitudinal magnetic field as a function of time for one of the representative points. The black line represents the fit to the data. The three vertical lines denote the start, peak, and end of the flare according to GOES X-ray flux measurements. The vertical axis spans 300 G, and tick marks appear at an interval of 50 G. The horizontal axis spans 240 minutes, and tick marks appear at an interval of 30 minutes.
Magnetic Field Changes during Solar Flares continued

of less than ten minutes. In about two-thirds of the cases, the longitudinal magnetic field decreased, in the remaining cases, the field increased. Most field changes occurred in the penumbras of sunspots. In six cases, the change in the magnetic field appears to have propagated across the active region. The rates of propagation range from 5 to 30 km s\(^{-1}\).

Because the full field vector is not observed, the interpretation of these results is ambiguous. Among several possible scenarios, we favor one in which the observed change in the longitudinal field is a result of the vector field becoming more vertical as an immediate consequence of the flare. If our favorite scenario is correct, work is associated with the tilting of the field, and this work must be included in the energy budget of any theory. Because the field changes always occur after the flare start, it is likely that the observed field changes are just one of the numerous post-flare phenomena and not the event that triggers flares. Still, the observed field changes may help sort out the basic physics of the flare phenomenon. This work contradicts current theories that posit that the photospheric magnetic field does not change during a flare. Extensions to our work will cover more events by relaxing our selection criteria and including weaker events.

The Spatial Distribution of Sodium on Mercury

*Drew Potter (NSO) & Rosemary Killen (University of Maryland)*

We are mapping the sodium emission from planet Mercury using the McMath-Pierce Solar Telescope, a 10-arcsec-square image slicer, and the stellar spectrograph. We obtain sodium images that are 10 arcsec square with 1-arcsec pixels. Since 1997, we have accumulated approximately a thousand of these images, covering a nearly complete range of true anomaly angles. The reason for collecting so many images is that the sodium distribution over the planetary surface is variable, sometimes from one day to the next. We expect that analysis of these variations will lead to a better understanding of the processes that govern the interaction of the space environment with planetary surfaces.

Figure 1 shows four sodium images that represent the most common kinds of sodium distribution. Figure 1a (upper left) shows limb brightening, resulting from an approximately uniform distribution of sodium vapor in the Mercury atmosphere. The long path length through sodium vapor above the planetary limb yields an image with bright sodium emission along the limb. Figure 1b (upper right) shows dawn-side enhancement of sodium. For this case, we are viewing the dawn terminator. As the sun rises, sodium that has condensed on the cold dark side of the planet is warmed, and evaporates into the atmosphere, leading to excess sodium on the dawn side. An additional dawn-side effect is the precipitation of sodium photo-ions to the surface, which some theoretical models predict should occur mostly in the dawn hemisphere (Killen et al. 2004, *Icarus*, 171, 1). Figures 1c and 1d show another sodium distribution effect, in which we see excess sodium in either the northern hemisphere (figure 1c) or the southern hemisphere (figure 1d).

The simplest quantity that we can use to characterize the distribution patterns illustrated in figure 1 is the ratio of the total sodium intensity from one hemisphere to the other. We calculated north-south and east-west ratios, using the brightest pixel in the surface reflection image as the center of the image. The north-south ratios are plotted against true anomaly angle in figure 2.

![Figure 1. Sample distributions of sodium on the surface of Mercury. Figure 1a is a limb-brightened image, as expected for a uniform distribution of sodium. Figure 1b shows sodium emission extending to the dawn terminator, and figure 1c and 1d show northern and southern hemisphere excess sodium, respectively.](image_url)
Spatial Distribution of Sodium on Mercury continued

Each data point represents the average of ten or more images taken on one day, with a standard deviation of about 10%, represented by the dashed lines. For perfectly symmetric distributions, such as seen for limb brightening in figure 1a, the ratio should be unity, or very close to it. In fact, most of the ratios are near unity. However, about a third of the ratios show excess sodium either in the north or south, with southern excess predominating over northern excess by a factor of about two. We suggest that the excess sodium seen in the northern or southern hemispheres is the result of sputtering of sodium from surface rocks by direct impact of the solar wind on the surface. Sarantos et al. (2001, Planet. Space Sci., 49, 1629) have shown that open field lines can connect with Mercury's surface at high latitudes, and their number and hemispheric locations depend on values of the Interplanetary Magnetic Field (IMF). Equally important is the fact that heavy stripped ions in the solar wind are extraordinarily efficient sputtering agents, as shown by Shemansky (2003, AIP Conf. Proc., 63, 687).

We also plotted the north-south ratio against longitude of the brightest point in the image, in the expectation that if there were some correlation of sodium emission with geological formations, we would see a clump of excess north or south sodium at that location. Results for this were inconclusive—there were no clear-cut longitudes where emission was consistently in excess in one hemisphere or the other. Better spatial resolution images are needed to resolve this question.

The east-west ratios showed some interesting features. The plot of east-west ratios against true anomaly angle for dawn-side images is shown in figure 3.

The geometry of Mercury observations is such that the dawn terminator is in view whenever Mercury is seen east of the Sun. Then the terminator is on the east side of the planet as seen in the sky, so that if there is a strong dawn enhancement, we expect that the ratio of east to west to be equal to or greater than unity. However, at true anomaly angles near zero, there should be little or no dawn enhancement from sodium evaporation, because the terminator is moving very slowly, and in fact reverses direction for a few days. Consequently, we might expect to find a ratio less than unity near zero true anomaly angles, but the observed ratios are actually slightly greater than unity. Perhaps this is the result of photo-ion precipitation on the dawn hemisphere.

As the true anomaly angle increases, accompanied by increasing terminator velocity that is moving condensed sodium into sunlight, the ratio increases as expected, rising to values as high as 1.6 near 120°. However, at larger angles, the ratio quickly drops below unity, suggesting that the dawn enhancement effect has disappeared. We speculate that the locus of sodium evaporation may move toward the limb as Mercury's surface temperature decreases with increasing distance from the Sun, which might explain this effect. Another speculation is that there might be changes in the electric field that control ion recycling, resulting in a switch from one favored hemisphere to the other.

We believe that our sodium distribution data support the concept that sputtering of surface rocks by the solar wind is a significant process on Mercury. Our data also support the existence of the dawn enhancement observed by Sprague et al. (1997, Icarus, 129, 506), but its variation with true anomaly angle presents some as-yet unexplained features.