

## 2010 SAO Summer Intern Project Abstracts

### Testing Stellar Evolution Theory with the Binary Fraction of Low-Mass White Dwarfs

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We describe spectroscopic observations of 21 low-mass ( $< 0.45M_{\odot}$ ) white dwarfs from the Palomar-Green Survey obtained over a period of four years. We use both radial velocity analysis and infrared photometry to identify binary systems, and find that the fraction of single, low-mass white dwarfs is 30 with an uncertainty of 18%. We discuss the inverse relationship between the mass and the binary fraction of white dwarfs and compare this relationship to existing theoretical models. We also compare the period distribution of 0.2 and 0.4 solar mass white dwarfs and find that lower mass white dwarfs have systematically shorter orbital periods. Our results support the idea that single low-mass white dwarfs can be formed through enhanced mass-loss from a metal-rich progenitor star. This work is supported in part by the NSF REU and DOD ASSURE programs under NSF grant no. 0754568 and by the Smithsonian Institution.

### Multi-Transiting Systems and Exoplanet Mutual Events

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Until recently, studies of transiting exoplanets- planets that cross in front of their host star- have focused almost exclusively upon systems where there is only one transiting planet. Those studies that have considered additional planets have mostly done so with the goal of determining the perturbing effects that additional planets would have upon the orbit, and therefore the light curve, of the transiting planet. This work considers, in detail, a specific type of event known as an exoplanet mutual event. Such events occur when one planet passes in front of another. While such events can occur whether or not these planets are transiting, predicting and understanding these events is best done in systems with multiple transiting planets. We estimate, through an ensemble simulation, how frequently exoplanet mutual events occur and which systems are most likely to undergo exoplanet mutual events. We also investigate what information can be learned about not only the planets themselves but also the orbital architecture in such systems. We conclude that while ODT (overlapping double-transit) events occur with a much lower frequency than PPO (planet-planet occultation) events, ODT mutual events are capable of producing detectable signals, that Kepler will detect a few, and recommend that candidate systems for such events, such as KOI 191 be observed in the short cadence (Steffen et. al 2010, Holman et. al 2010). This work is supported in part by the NSF REU and DOD ASSURE programs under NSF grant no. 0754568 and by the Smithsonian Institution.

## **Fornax A's Western Radio Lobe Composition**

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We present an analysis of the western radio lobe of Fornax A based on an XMM-Newton observation. We find little evidence for the inverse-Compton scattering of the cosmic microwave background as reported previously. The spectra in the energy range of 0.5–5 keV are well fitted by a thermal plus power law model for every spectral region we extracted. With a fixed photon index of 1.68, the X-ray flux density at 1 keV from the power law fit was measured to be  $< 28$  nJy at the 90% confidence level, leading to a lower limit on the magnetic field in this region of  $6 \mu\text{G}$ . Our spectral fits suggest that there is hot gas surrounding the radio lobe. A filament of dense, cool gas extends from the central galaxy in the direction of the radio lobe of Fornax A. Spectral fits give a temperature of  $kT = 0.76$  keV over the radio lobe and  $kT = 0.32$  keV for the cool filament. The thermal emission from the radio lobe region is best explained as emission from a thin shell of shocked gas swept up by the rapidly expanding lobe. This work is supported in part by the NSF REU and DOD ASSURE programs under NSF grant no. 0754568 and by the Smithsonian Institution.

## **New Methods for Identifying Nearby Gravitational Lenses in All-Sky Surveys**

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All-sky catalogs provide a wealth of information about gravitational lensing events that has not yet been utilized. We present a method for matching lensing events to catalogs and finding the probability that the association is genuine. Given a likely candidate for the lens object associated with an event, it is possible to break the inherent degeneracy in microlensing and estimate the mass of the lens, depending on its distance. Eight percent of microlensing events have matches in the 2MASS catalog, and there are many more matches in catalogs that cover other wave bands. In addition to detecting the associated lens or source, it is possible that the cataloged object is a companion or host to the actual lens. This opens up the possibility of finding dark nearby lenses, such as stellar remnants or planets that are associated with cataloged objects. We propose various methods for determining which events are most likely to be caused by nearby lenses, and apply them to our matches. We present some interesting matched objects and the results of observations of those objects. This work is supported in part by the NSF REU and DOD ASSURE programs under NSF grant no. 0754568 and by the Smithsonian Institution.

## **A New Digital S Star Atlas and Its Uses**

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S and carbon (C) stars are traditionally thought to be on the asymptotic giant branch because of their high C/O ratios and enhanced s-process elements. A sample of S stars at high Galactic latitudes would help us understand their formation and evolution in disk to halo populations, at a variety of metallicities and with minimal reddening. Faint S stars would either be at large Galactocentric radii, or dwarfs. S dwarfs are in analogy to dwarf C stars, which are thought to originate from mass transfer in a binary system. Dwarf C stars are now known to be the numerically dominant type of C star in the Galaxy, but no S dwarfs have ever been found. Their discovery and knowledge of their space density could closely constrain some of the many available channels of binary evolution. The Sloan Digital Sky Survey (SDSS) seems an ideal place to find faint S stars, but the colors of these stars are largely unknown, since all known S stars (median V magnitude of  $\sim 10.5$ ) are saturated in the SDSS. We use the FAST spectrograph on the Tillinghast reflector on Mt. Hopkins to obtain the spectra of 57 known S stars that appear in the Two-Micron All Sky Survey (2MASS). We flux calibrate these spectra, provide them electronically as a digital atlas, and convolve them with SDSS bandpasses to generate likely colors for S giants and dwarfs. We find that these S star colors are not clearly distinguished from the colors of M giants and C stars. We also present initial results of a cross-correlation with the SDSS spectral database, using the FAST spectra as templates. This work is supported in part by the NSF REU and DOD ASSURE programs under NSF grant no. 0754568 and by the Smithsonian Institution.

## **Massive Star Formation in the Cygnus-X Region**

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Massive stars shape galaxy evolution and nearby star formation through feedback mechanisms, yet many aspects of how they form and how they evolve towards the zero-age-main-sequence are still a mystery. The Cygnus-X region contains many massive young stellar objects (YSOs), and at only a distance of 1.7 kpc, this complex is ideal for studying massive star formation. We have observed a list of 25 sources with the IRS, basing our source selection on candidates previously identified in the Cygnus-X Spitzer Legacy Survey using the MIPS and IRAC instruments, the IRAM 1.2 mm survey of the region, and combining these with some older infrared surveys. Common features in the spectra include molecular hydrogen lines tracing shocks at the HII region boundary, polycyclic aromatic hydrocarbon emission in the HII region, and carbon dioxide ice absorption in the envelope. Silicate absorption is also present, allowing us to determine interstellar extinction to the sources. Neon and sulfur forbidden emission lines from ionized gas were also detected. Using the objects' spectral energy distributions, along with line flux ratios derived from the new IRS spectra, we fit models of YSOs to derive stellar mass, age, and temperature, as well as total luminosity of the system, envelope accretion rate of mass onto the stars, and other physical parameters. This work is supported in part by the NSF REU and DOD ASSURE programs under NSF grant no.

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## **Radial Distribution of Molecules and Ions in the Protoplanetary Disk Around IM Lup**

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We present spatially and spectroscopically resolved Submillimeter Array (SMA) observations of  $^{12}\text{CO}$  J=2-1,  $^{13}\text{CO}$  J=2-1,  $\text{DCO}^+$  J=3-2,  $\text{N}_2\text{H}^+$  J=3-2, and  $\text{H}_2\text{CO}$  J=4(14)-3(13) line emission from the IM Lup protoplanetary disk. We use Monte Carlo radiative transfer calculations to compare the SMA visibilities with tapered disk models, and use the results to constrain the outer radii of the emission regions.  $\text{N}_2\text{H}^+$  and  $\text{H}_2\text{CO}$  are proposed to trace dust grains at temperatures below 20 K, and  $\text{DCO}^+$  are proposed to trace gas temperatures below 40 K. The inferred outer radii for  $\text{N}_2\text{H}^+$  and  $\text{H}_2\text{CO}$  are both 600 AU, and 300–600 AU for  $\text{DCO}^+$ . These values are consistent with thermally decoupled gas and dust in the outer disk. This work is supported in part by the NSF REU and DOD ASSURE programs under NSF grant no. 0754568 and by the Smithsonian Institution.

## **The Dynamical State of the Telescopium Galaxy Group - Deep Chandra Observations of NGC 6868 and NGC 6861**

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We present results from deep Chandra observations of NGC 6868 and NGC 6861, the two dominant elliptical galaxies in the Telescopium galaxy group (Abell S0851). We examine the diffuse gas in and around these galaxies to establish the possible interactions occurring within the group. Surface brightness images exhibit bright edges and tails, which indicate that the galaxy group is not dynamically relaxed. Spectral analysis reveals a spiral of cool gas with an associated cold front edge in NGC 6868, indicative of gas sloshing initiated by a passing galaxy or subgroup. NGC 6861 shows bright, swept back arms and a broad tail of emission, both to the northwest, suggesting that it is being ram pressure stripped due to interactions with a diffuse intracluster medium as it moves to the southeast. We find evidence that the arms are composed of cool gas originating from the galaxy core, and propose that, as seen in other systems, they may be filaments that have been buoyantly lifted by putative radio lobes inflated by the central AGN. Our results are consistent with previous suggestions that NGC 6868 and NGC 6861 are the central dominant members of two distinct subgroups, which are currently merging to form the Telescopium galaxy group. This work is supported in part by the NSF REU and DOD ASSURE programs under NSF grant no. 0754568, by Chandra grant GO0-1009X issued under NASA contract NAS8-03060, and by the Smithsonian Institution.

## Radio Observations Reveal the Mass Loss History of Type Ibc Supernova Progenitors

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We present extensive radio observations of the nearby Type Ibc supernovae 2004cc, 2004gq, and 2004dk spanning  $\Delta t \approx 8 - 1800$  days after explosion. Using a dynamical model developed for synchrotron emission from a slightly decelerated blastwave, we estimate the velocity and energy of the fastest ejecta and the density profile of the circumstellar medium. The blastwaves for all three supernovae are characterized by non-relativistic velocities of  $v \approx (0.1 - 25)c$  and associated energies of  $E \approx (2 - 10) \times 10^{47}$  erg, in line with the expectations for a typical homologous explosion. Smooth, stellar wind density profiles are indicated by the early radio data and we estimate the progenitor mass loss rates to be  $\dot{M} \approx (8 - 40) \times 10^{-6} M_{\odot} \text{ yr}^{-1}$  (wind velocity,  $v_w = 103 \text{ km s}^{-1}$ ). These properties are consistent with those of Wolf-Rayet stars, the favored progenitors of SNe Ibc including those associated with long-duration gamma-ray bursts. However, at late time, each of these SNe show evidence for abrupt radio variability which we attribute to significant circumstellar density modulations (factor of  $\sim 5 - 100$ ) at radii of  $R \approx (1 - 50) \times 10^{16} \text{ cm}$ . For SN 2004gq, the density modulations are marginally consistent with the expectations for a variable and/or clumpy Wolf-Rayet line-driven wind. However, in the case of SNe 2004cc and 2004dk, the density modulations are more intense,  $\dot{M} \gtrsim 10^{-4} M_{\odot} \text{ yr}^{-1}$ , and possibly attributed to continuum-driven winds or hydrodynamic eruptions. We compare the circumstellar environments for these three SNe with those of other Type Ibc supernovae and nearby gamma-ray bursts and find that they are characterized by a more violent progenitor mass loss history in the decades leading up to explosion. This work is supported in part by the NSF REU and DOD ASSURE programs under NSF grant no. 0754568 and by the Smithsonian Institution.

## Investigating the Dynamical History of the Solar System

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The current dynamical structure of the Kuiper belt was shaped by the evolution of giant planet orbits during the era of planet formation. Numerical models of this process, while reproducing many properties of the belt, have difficulty generating the high inclinations and eccentricities observed for some objects while maintaining a low eccentricity and low inclination "cold classical" population. We present a parameter study of the effect of different dynamical histories on orbits in the Kuiper belt using N-body simulations. In particular, we probe which combinations of migration, eccentricity damping, and inclination damping of Neptune over the history of the solar system allow the cold classical population to survive. This work is supported in part by the NSF REU and DOD ASSURE programs under NSF grant no. 0754568 and by the Smithsonian Institution.