The Catholic University of America
Institute for Astrophysics and Computational Sciences
Department of Physics

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The following report covers the astrophysical research activities of the Institute for Astrophysics and Computational Sciences (IACS) and other closely related research activity in the Department of Physics for the period from September 1999 through September 2000. IACS has three major areas of concentration: a) Basic Astrophysics & Planetary Physics, b) Imaging Technology and c) Solar & Solar-terrestrial Physics. The IACS was established in October 1996 to a) develop strong research and educational programs in the areas of astrophysics and computational sciences at CUA, and b) promote closer cooperation between CUA and government agencies and with industry. This has been done to take advantage of CUA's proximity to major laboratories and its existing collaborations with government and private enterprise. The ultimate goal is to enhance research, educational, and employment opportunities for CUA faculty, research staff, and students over what is typically offered in the academic environment. The IACS operates in the Department of Physics at CUA.

1 PERSONNEL

The Ph.D. faculty and research staff directly affiliated with the Institute are: Fred Bruhweiler (Director), Vladimir Airapetian, Al Boggess, Tom Brown, Peter Chen, Mike Crenshaw, Mike DiSanti, Mike Goodman, Nat Gopalswamy, Rosina Iping, Leon Ofman, Scott Johnson, Steve Kraemer, Alejandro Lara, C.-H. Lyu, Tom Moran, Charles Proffitt, Rich Robinson, Meena Sahu, Myron Smith, Margaret Smith Neubig, O. C. St. Cyr, Masahiro Tanaka, Glenn Walhgren and Seiji Yashiro. Other Ph.D. members of the Dept. of Physics participating in astrophysical research, working closely with IACS, include Pamela Clark, Neale Dello Rosso, Sarah Gibson, M. Guhathakurta, Vladimir Krasnopolsky, Fred Lang, Richard Starr and Carl Werntz. Adjunct Professors at CUA, who are also members of IACS or working closely with it, include Yoji Kondo, Andrew Smith, and Carol Jo Crannell.

Non-Ph.D. research and support staff, who work directly in the IACS, are Tena DuBerry, and Cherie Miskey, as well as the graduate students, Jack Gabel, Joseph Goyette, Charles Hall, Theo Hadjimichael, Ian Liska, John Nichols, Steve Nunes, Timothy Maloney, Jose' Ruiz, Edward Wassell, Scott Weingarten, and Linhui Sui. This is in addition to undergraduate students (Matt Austin (CUA), Luis Henriques (US Nav. Acad.), Kathyrn Holz-Donohue (CUA), Annie James (CUA), Matt Lemmon (N. Arizona State), Mark Pitts (Ohio State), Mike Salem (Case Western Reserve University), Joseph Gordon (University of Pennsylvania), and a talented high school student, Timothy Daniels (Da Matha HS), who have participated in scientific research with members of the Institute during this period.

Within IACS, in addition to the curriculum in Astrophysics, the Center for Solar Physics and Space Weather (CSPSW) has initiated an educational curriculum in the area of Space Weather. The core members of CSPSW are N. Gopalswamy (Curriculum Head), A. Poland (NASA/GSFC), R. A. Howard (NRL), S. Jordan (NASA /GSFC), D. Rust (JHU/APL), J. Green (NASA/ GSFC), D. Sibeck (JHU/APL), C. Crannell (GSFC), M. Guhathakurta, A. Lara Sanchez, T. Moran, O. C. St. Cyr and S. Yashiro.

During this period, Jack Gabel received his Ph.D. under Bruhweiler's direction.

2 RESEARCH ACTIVITIES IN ASTROPHYSICS

2.1 Galaxies & Extragalactic Astronomy

Bruhweiler, along with Miskey, and Smith Neubig, and Alex de Koter (Amsterdam), Nolan Walborn (STScI), and Thierry Lanz (GSFC/AURA) continue to use Hubble Space Telescope spectra to study the effects of metallicity on properties of massive stars and starburst activity in galaxies of the Local Group. The goals are to use UV spectra to: a.) determine the photospheric abundance patterns in the young stars of the different galaxies, b.) determine how metallicity affects the characteristics (mass loss rate and terminal velocities) of the mass outflow, and c.) derive the nature of the dust extinction laws in regions where pronounced starburst activity is observed. Smith Neubig and Bruhweiler have just completed analysis of the HST spectra for all the ultraviolet GHRS and FOS spectra for stars in the SMC and LMC. These results confirm their earlier findings and establish more definite spectral classification criteria for stars in low metallicity environments. This work also revealed a before unrecognized intrinsic stellar UV absorption troughs that has been masked by the attenuation of interstellar dust. Recent HST/STIS two-dimensional spectral imagery have been obtained by Bruhweiler, Miskey, de Koter, Walborn, and Smith Neubig for young OB associations in Sextans A, NGC 6822, and for the core of 30 Dor in the LMC. The spectra obtained for the O and B stars in Sextans A sample the lowest metallicity O and B stars (1/30 Solar abundance) for which individual UV spectra have been obtained. This metallicity is only a factor of two higher than that of I Zw 18, which is the most metal deficient galaxy known. The spectra of the Sextans A stars show significantly weaker N V, C IV, and Si IV UV mass loss profiles than in analogous SMC stars. An analysis using sophisticated model atmospheres has commenced. Analysis of the Sextans A and NGC 6822 data are well underway. Additional scheduled HST two-dimensional spectra of the SMC and LMC are expected to yield UV through visual spectra for over 300 individual OB stars. Bruhweiler, Miskey and Smith Neubig are preparing two papers for publication that describe the newly developed spectral extraction technique for STIS 2-D data and also its application for one of the brightest H II regions in the Local Group, NGC 604 in M 33. The extraction technique has been shown to provide significantly better spectral resolution than the standard STScI pipeline processing. This has important implications for all observations using the STIS aboard the HST. Analysis of the STIS data for core of NGC 604 reveal five luminous W-R stars. The luminosities and spectral types of these stars along with other early type O stars in NGC 604 imply an age of 3-4 Myr for the most recent phase of star formation.

Crenshaw, Kraemer, Hutchings (DAO), Bradley, Gull (GSFC), Kaiser (JHU), Nelson (UNLV), Ruiz, & Weistrop (UNLV) have developed a simple kinematic model for the narrow-line region (NLR) of the Seyfert 1 galaxy NGC 4151, based on our previous observations of extended [O III] emission with the Space Telescope Imaging Spectrograph (STIS). The model is similar to a biconical radial outflow model developed for the Seyfert 2 galaxy NGC 1068, except that the bicone axis is tilted much more into our line of sight (40 degrees out of the plane of the sky instead of 5 degrees), and the maximum space velocities are lower (750 km s^{-1} instead of 1300 km s^{-1}). We find evidence for radial acceleration of the emission-line knots to a distance of 160 pc, followed by deceleration that approaches the systemic velocity at a distance of 290 pc (for a distance to NGC 4151 of 13.3 Mpc). Other similarities to the kinematics of NGC 1068 are: 1) there are a number of high-velocity clouds that are not decelerated, suggesting that the medium responsible for the deceleration is patchy, and 2) the bicone in NGC 4151 is at least partially evacuated along its axis. Together, these two Seyfert galaxies provide strong evidence for radial outflow (e.g., due to radiation and/or wind pressure) and against gravitational motion or expansion away from the radio jets as the principal kinematic component in the NLR.

Crenshaw, Kraemer, Hutchings (DAO), Danks, Gull (GSFC), Kaiser (JHU), Nelson (UNLV), and Weistrop (UNLV) have published their first results on echelle observations of the intrinsic UV absorption lines in the Seyfert galaxy NGC 4151, which were obtained with the Space Telescope Imaging Spectrograph (STIS) on the Hubble Space Telescope (*HST*) on 1999 July 19. The UV continuum flux at 1450 Å decreased by factor of about four over the previous two years and there was a corresponding dramatic increase in the column densities of the low-ionization absorption lines (e.g., Si II, Fe II, and Al II), presumably as a result of a decrease in the ionizing continuum. In addition to the absorption lines seen in previous low states, we identify a large number of Fe II absorption lines that arise from metastable levels as high as 4.1 eV above the ground state, indicating high densities ($> 10^6$ cm^{-3}). We find that the transient absorption feature in the blue wing of the broad C IV emission, seen in a Goddard High Resolution Spectrograph (*GHRS*) spectrum and thought to be a high-velocity C IV component, is actually a Si II fine-structure absorption line at a radial velocity of -560 km s^{-1} (relative to systemic). We also demonstrate that the ‘‘satellite’’ emission lines of C IV found in International Ultraviolet Explorer (*IUE*) spectra are actually regions of unabsorbed continuum plus broad emission that become prominent when the UV continuum of NGC 4151 is in a low state.

Crenshaw and Kraemer have obtained the first long-slit spectra of the Seyfert 2 galaxy NGC 1068 with the Space Telescope Imaging Spectrograph (STIS); the spectra cover the wavelength range 1150 – 10,270 Å at a spatial resolution of 0.05 – 0.1″ and a spectral resolving power of $\lambda/\Delta\lambda \approx 1000$. In the first paper, we concentrated on the far-UV to near-IR continuum emission from the continuum ‘‘hot spot’’ and surrounding regions extending out to $\pm 6.0''$ (± 432 pc) at a position angle of 202 degrees. In addition to the broad emission lines detected by spectropolarimetry, the hot spot shows the ‘‘little blue bump’’ in the 2000 – 4000 Å range, which is due to Fe II and Balmer continuum emission. The continuum shape of the hot spot is indistinguishable from that of NGC 4151 and other Seyfert 1 galaxies. Thus, the hot spot is reflected emission from the hidden nucleus, due to electron scattering (as opposed to wavelength-dependent dust scattering). The hot spot is $\sim 0.3''$ in extent and accounts for 20% of the scattered light in the inner 500 pc. We are able to deconvolve the extended continuum emission in this region into two components: electron-scattered light from the hidden nucleus (which dominates in the UV) and stellar light (which dominates in the optical and near-IR). The scattered light is heavily concentrated towards the hot spot, is stronger in the northeast, and is enhanced in regions of strong narrow-line emission. The stellar component is more extended, concentrated southwest of the hot spot, dominated by an old ($\geqslant 2 \times 10^9$ years) stellar population, and includes a nuclear stellar cluster which is ~ 200 pc in extent.

In their second paper on the STIS spectra of NGC 1068, Kraemer and Crenshaw examined the physical conditions near the optical continuum peak (‘‘hot spot’’) in the inner narrow line region (NLR). The spectra show emission-lines from a wide range of ionization states for the most abundant elements, similar to archival Faint Object Spectrograph spectra of the same region. Perhaps the most striking feature of these spectra is the presence of strong coronal emission lines, including [S XII] λ7611 which has hitherto only been identified in spectra of the solar corona. There is an apparent correlation between ionization energy and velocity of the emission lines with respect to the systemic velocity of the host galaxy, with the coronal lines blueshifted, most other high excitation lines near systemic, and some of the low ionization lines redshifted. From the results of our modeling, we find that the emission-line gas is photoionized and consists of three principal components: 1) one in which most of the strong emission-lines, such as [O III] λ5007, [Ne V] λ3426, C IV λ1550, arise, 2) a more tenuous, highly ionized component, which is the source of the coronal-line emission, and 3) a component, which is not co-planar with the other two, in which the low ionization and neutral lines, such as [N II] λ6548 and [O I] λ6300, are formed. The first two components are directly ionized by the EUV-Xray continuum emitted by the central source, while the low ionization gas is ionized by a combination of highly absorbed continuum radiation and a small fraction of unabsorbed continuum scattered by free electrons associated with the hot spot. The combination of covering factor and Thomson optical depth of the high ionization components is insufficient to scatter the observed fraction of continuum radiation into our line-of-sight. Therefore, the scattering must occur in an additional component of hot plasma, which contributes little or no UV/optical line emission.

In their third paper on the STIS spectra of NGC 1068, Kraemer and Crenshaw examined the physical conditions in the inner narrow line region (NLR). We have measured the emission-line fluxes for a region extending 3.8″ northeast ($\sim$ 270 pc) to 1.8″ southwest ($\sim$ 130 pc) of this point. The emission-lines on each side show evidence of two principal kinematic components, one blueshifted with respect to the systemic velocity and the other redshifted (the kinematics were discussed in a separate paper). Based on the photoionization modeling results we find that the physical conditions vary among these four quadrants. 1) The emission-line gas in the blueshifted northeast quadrant is photoionized by the hidden central source out to $\sim$ 100 pc, at which point we find evidence of another source of ionizing radiation, which may be due to fast ($\sim$ 1000 km s^{-1}) shocks resulting from the interaction of the emission-line knots and the interstellar medium. Interestingly, this occurs at approximately the location where the knots begin to show signs of deceleration. 2) The gas in the redshifted northeast quadrant is photoionized by continuum radiation that has been heavily absorbed by gas within $\sim$ 30 pc of the central source. We find no strong evidence of the effects of shocks in this component. 3) The redshifted emission-line gas in the southwest quadrant is photoionized by unabsorbed continuum from the central source, similar to that in the inner $\sim$ 100 pc of the blueshifted northeast quadrant. Finally, 4) the emission-line spectrum of the blueshifted southwest quadrant appears to be the superposition of highly ionized, tenuous component within the ionization cone and gas outside the cone, the latter photoionized by scattered continuum radiation. There are several implications of this complicated physical scenario. First, the hidden active nucleus is the dominant source of ionizing radiation in the inner NLR. The absorption of continuum radiation along the line-of-sight to the redshifted northeast quadrant may result from the intersection of the ionization cone and the plane of the host galaxy. Finally, the evidence for shock-induced continuum radiation at the point where the emission-line knots begin to decelerate indicates that the deceleration is due to the interaction of emission-line knots with slower moving gas, such as the interstellar medium of NGC 1068.

In their fourth paper on the STIS spectra of NGC 1068, Crenshaw and Kraemer determined the radial velocities of the [O III] emitting gas in the inner NLR. We used these data to investigate the kinematics of the NLR within 6″ ($\sim$430 pc) of the nucleus. The emission-line knots show evidence for radial acceleration, to a projected angular distance of 1.7″ in most cases, followed by deceleration that approaches the systemic velocity at a projected distance of $\sim$4″. We find that a simple kinematic model of biconical radial outflow can match the general trend of observed radial velocities. In this model, the emitting material is evacuated along the bicone axis, and the axis is inclined 5 degrees out of the plane of the sky. The acceleration of the emission-line clouds provides support for dynamical models that invoke radiation and/or wind pressure. We suggest that the deceleration of the clouds is due to their collision with a patchy and anisotropically distributed ambient medium. The presence of enhanced reflected continuum emission near the velocity turnover points suggests that this medium is highly-ionized low-density gas with a large filling factor at these distances.

Kraemer, Crenshaw, Hutchings (DAO), Gull (GSFC), Kaiser (JHU), Nelson (UNLV), and Weistrop (UNLV) have examined the physical conditions in the narrow-line region of the well-studied Seyfert galaxy NGC 4151, using long-slit spectra obtained with the STIS. The data were taken along a position angle of 221 degrees, centered on the optical nucleus. We have generated photoionization models for a contiguous set of radial zones, out to 2.3″ in projected position to the southwest of the nucleus, and 2.7″ to the northeast. Given the uncertainties in the reddening correction, the calculated line ratios successfully matched nearly all the dereddened ratios. We find that the narrow-line region consists of dusty atomic gas photoionized by a power-law continuum that has been modified by transmission through a mix of low and high ionization gas, specifically UV and X-ray absorbing components. The physical characteristics of the absorbers resemble those observed along our line of sight to the nucleus, although the column density of the X-ray absorber is a factor of ten less than observed. The large inferred covering factor of the absorbing gas is in agreement with the results of our previous study of UV absorption in Seyfert 1 galaxies. We find evidence, specifically the suppression of L α, that we are observing the back-end of dusty ionized clouds in the region southwest of the nucleus. Since these clouds are blueshifted, this supports the interpretation of the cloud kinematics as being due to radial outflow from the nucleus. We find that the narrow-line gas at each radial position is inhomogeneous, and can be modeled as consisting of a radiation-bounded component and a more tenuous, matter-bounded component. The density of the narrow-line gas drops with increasing radial distance, which confirms our earlier results, and may be due to the expansion of radially outflowing emission-line clouds.

Gabel and Bruhweiler have just completed the modeling of the starburst/LINER galaxy, NGC 4569. The UV spectrum revealed in the HST data shows a very luminous starburst of very young O star population. The population synthesis modeling results indicate a starburst age of 4-5 Myr with a solar or super-solar metallicty. The age estimate is in accord with the previous less detailed results of Barth *et al.* Yet, these results place very stringent constraints on the number of Wolf-Rayet stars that are present in this exceedingly luminous star-forming region. The upper limits for the number of W-R stars as deduced from the He II λ1640 and C IV $\lambda\lambda$1548,1550 also places an upper limit of the EUV ionizing flux. The upper limits for the number of W-R stars is contrary to what is expected from predictions of stellar evolution. Further modeling, using the code CLOUDY, indicates that stellar photoionization alone may be insufficient alone to produce the observed nebular emission associated with this object. Additional collisional ionization is implied from supernovae produced by the massive stars in the nuclear starburst. Based upon the low level of radio emission and power-lay continuum, there is no evidence for an embedded AGN in NGC 4569.

2.2 Interstellar Medium

Bruhweiler, Lyu, and A. Smith have tentatively identified the molecule CH_2 in the UV spectrum of the stars HD 154368 and ζ Oph. These results come from analysis of the HST high dispersion spectral data. The derived tentative column densities are 4 and 7 times 10^{13} cm^{-2}, respectively. These values are within a factor of two of the predicted values for the carbon chemistry reaction network predictions.

Sahu, Bruhweiler, Holberg (Arizona), Barstow (Leichester), Linsky (JILA), and Landman(Raytheon/ITSS) continue their combined analysis of new and archival data from HST and the Far-Ultraviolet spectral Explorer (FUSE) in an attempt to map out the distribution of neutral and ionized gas within $\approx$ 100 pc of the sun. Results published in Sahu et al. do not support variation in the D/H ratio reported in previous investigations. Further, new observations to accurately determine the D/H ratio and ionic column densities of heavier ions toward nearby white dwarfs are scheduled with the HST.

2.3 Stellar Physics

Airapetian and Robinson, in collaboration with Ofman (Raytheon), Carpenter and Davila (NASA/GSFC) completed a theoretical investigation of whether the winds on cool giant and supergiant stars can be driven with non-linear Alfven waves. In these numerical simulations they assume a longitudinally uniform density distribution with a hydrostatic pressure scale height of 0.072 $R_\star$, an isotropic, radial magnetic field with an Alfven speed of 92 km s^{-1} at the surface and and a wave period of 76 days, which roughly corresponds to the convective turnover time. The calculations produce a wind with a terminal velocity of about 22 km s^{-1} and a mass loss rate of about 10^{-6} M_{solar} yr^{-1}, which is comparable to observations.

Robinson, in collaboration with Bohm-Vitense (U Washington) and others, completed a study of Barium stars using UV spectra obtained with the HST. Current theory suggests that the peculiar abundances found on these late-type, giant stars are the result of mass transfer during the evolution of a companion. If this theory is correct, then the Barium stars should all have a white dwarf (WD) companion, which would be detectable in the UV. The targets included 4 normal barium and 3 weak barium stars. It was found that most of these stars had an excess continuum in the UV when compared with standard giant stars. For most of these stars the excess flux is compatible with a WD companion with temperatures between 10,000 and 12,000 K. The calculated cooling times for several of these WDs is longer than the lifetimes of the barium stars on the giant branch, suggesting that in these cases the mass transfer occurred when the barium star was still on the main sequence. This is unlikely, however, since main-sequence barium stars are not observed. Thus, while the observations indicate that the mass transfer hypothesis is viable, we find that either evolutionary models with large convective overshoot have to be used for the barium stars or the cooling times of the white dwarfs have to be revised.

Robinson and Smith have also obtained additional X-ray (RXTE) data for γ Cas over two 1.1-day cycles. They found the X-ray fluxes repeat only roughly from one cycle to the next, implying that portions of archival X-ray data cannot be used to refine this ephemeris. The amplitudes of the flare-like ''shot'' component of this flux follow an exponential distribution, which is distinctly different than the power-law distribution observed for flares in active cool stars. In addition, these investigators find brief but robust interruptions every $\approx$7.5 hours in flare occurrences. The cause of this cycle is not yet understood. However, an unexpected discovery was that a 7.5-hour pattern was found in the blue-wings (DACs) of the resonance lines of Si IV and C IV of spectra of γ Cas. These wings are formed in the wind of this Be star, within a few stellar radii of its surface. This discovery demonstrates once again that the X-rays must be formed close to the stellar surface.

Robinson, Linsky (JILA), Woodgate (GSFC) & Timothy (Nightsen) have completed a study of UV flaring activity on the dMe star AU Mic using data obtained with the STIS aboard the Hubble Space Telescope. The data were taken using the Time-Tag observing mode, in which the location and time of each detected photon is recorded. This allows the spectral information to be examined on a variety of time scales. During the 10^4 s of observations, four moderate sized flares and $>$50 microflare bursts were observed. The larger events were all composed of groups of bursts, supporting the avalanche flare model. The occurrence rate for the flares showed a power law distribution, with the low energy events having a power law index greater than 1. This implies that these small events could play an important role in heating the stellar chromosphere. During the flares the Si IV and C IV lines, formed at temperatures between 8×10^4 and 10^5 K, experienced the greatest enhancements, with lines formed at both higher and lower being much less affected. This suggests that the temperature distribution formed within the flares was very sharply peaked. There was a substantial amount of Doppler broadening of the emission lines, but the effects were reasonably symmetric, with little indication of the unidirectional flows which are expected from an evaporation model. Finally, the UV continuum appears to be formed through the blending of numerous weak emission lines, rather than through a true b-f or f-f process.

Smith, Robinson, and colleagues have continued work on the B0.5e star γ Cas, a star which shows unusual properties of ubiquitous X-ray flaring and an extraordinary high plasma temperature ($\approx10^8$K) Their work over the previous two years was based on a program of simultaneous *Hubble/GHRS* and X-ray *RXTE* satellite observations of this star lasting a full day. These investigators concluded that (1) the X-rays are emitted from primarily two X-ray active regions on or near the star's surface, and (2) UV continuum flux minima at these same times are caused by the occultation of the star by a pair of co-rotating clouds forced into co-rotation over the star with a 1.123 day period. In the fourth paper of this series based on the same *GHRS* data, Cranmer, Smith, &

Robinson have examined the dependence of the high-velocity Discrete Absorption Components (''DACs'') of the star's Si IV λλ1394–1403 resonance lines. These authors have derived densities for the DAC-forming region that are intermediate between that of the star's equatorial decretion disk and mid-latitude, ambient wind. They also find that sub-features appear at low velocities and evolve to the blue with time, suggesting a spiral-shaped opacity enhancement which probably emanates from one of the two activity centers mentioned above. Several correlations of X-ray and UV flickering have been found in the data which can be found also in archival *IUE* and *Copernicus* satellite data. The *GHRS*, *IUE*, and *Copernicus* data demonstrate that the silicon and iron ionization equilibrium in the wind shifts to higher ionization states at times of increased X-ray flux. This is consistent with two major X-ray activity aggregates rotating into view, illuminating the wind in our line of sight.

3 SOLAR PHYSICS AND SUN-EARTH CONNECTION

Carol Jo Crannell and Sui (graduate student) are analyzing microwave flare data from the Owens Valley solar radio array. This study will be used for combined analysis of X-ray (from HESSI, to be launched in March 2001) and microwave data.

Cliver (Phillips Lab), Gopalswamy and St Cyr performed a statistical analysis of metric type II bursts and studied their relationship between CMEs and flares. They reevaluated several recent investigations and concluded that CME is a necessary pre-condition to the occurrence of a coronal shock. The question of whether a type II shock can result from a pure blast wave (no material ejection) remains open as does the question of the relative fraction of metric type II bursts with CMEs.

Gibson uses theoretical models as a framework on which to compare and connect solar coronal structures seen on multiple scales. She has undertaken this both for ''static'' coronal streamer structures and for dynamic structures such as coronal mass ejections (CMEs) and sigmoidal active regions, their potential precursors. She is presently analyzing data from the Whole Sun Month 3 campaign in August, 1999, which she coordinated with Biesecker, and from the Spartan white light coronagraph mission of November, 1998. Analysis of the Spartan data involves determining streamer boundaries, density and temperature distribution throughout the streamer, and streamer evolution over the 3 days of Spartan observation. Gibson is collaborating on this analysis with Fisher (GSFC), Fludra (GSFC), Guhathakurta and Kucera.

Her analysis of the WSM3 sigmoid data studies the evolution of the sigmoid during is solar disk passage, and considers its three-dimensional structure in detail. This work is mainly in collaboration with Mason, Pike, Del Zanna, and Fletcher. She recently published a theoretical interpretation of these sigmoidal CME precursors and associated filaments with Low. Gibson is also currently working with Guhathakurta developing 3-d tomographic models of CMEs and streamers, and MHD models of the solar wind and coronal magnetic field.

Gopalswamy, Kaiser (GSFC), Sato and Pick (Meudon, France) studied a metric type II burst and a 'brow' type enhancement in EUV during the hard X-ray flare of 1997 April 15 from a newly emerging region, AR 8032. The position of the type II burst obtained from the Nancay radioheliograph coincided with the EUV transient. The type II burst and the EUV transient were in the equatorial streamer region to the north of the flaring region. This observation suggests that the EUV transient may be the manifestation of the MHD shock responsible for the type II burst.

Gopalswamy, Kaiser (GSFC), Lara & Howard (NRL) validated the empirical CME arrival model of Gopalswamy *et al.* (2000). The model was based on a linear relationship between the effective acceleration and the initial speed of the CMEs obtained observationally. Recently, this model has been validated using historical data from the Helios-1, Pioneer Venus Orbiter and P78-1 missions. The effective acceleration was found to have similar linear relationship to the initial speed, except for a small change in the slope of the line. The CME speeds measured from the past missions are free from projection effects because of the orthogonal view points of these spacecraft and thus validated the empirical CME arrival model.

Gopalswamy and Thompson (GSFC) reviewed the early life of coronal mass ejections using X-ray, microwave and EUV images as well as white light observations from SOHO/LASCO. The study relies heavily on non-coronagraphic data combined with coronagraphic data. Specifically, we they explore the following aspects of CMEs: (i) coronal dimming and global disk signatures, (ii) nonradial propagation during the early phase, (iii) photospheric magnetic field changes during CMEs, and (iv) acceleration of fast CMEs. The relative positions and evolution of coronal dimming, arcade formation, prominence eruption is discussed using specific events. It is found that the magnitude and spatial extent of CME acceleration may be an important parameter that distinguishes fast and slow CMEs.

Gopalswamy, Moran and Wilhelm (Max Planck) are studying the relationship between the microwave enhancement in coronal holes and EUV signatures obtained by Solar and Heliospheric Observatory's (SOHO) SUMER instrument. In October 1999, an observing campaign was conducted with Nobeyama Radioheliograph and SOHO/SUMER. Since we expect that the microwave enhancement occurs over a narrow layer in the upper chromosphere, we observed coronal holes in low temperature lines (around 10000 K). Analysis of these observations will help us understand the reason for the coronal enhancement which has been a puzzle for a long time.

Gopalswamy, Kaiser (GSFC), Yashiro and Howard (NRL) have discovered radio evidence for ''CME cannibalism'' in the dynamic spectra of the Wind/WAVES experiment. They found that DH type II bursts show large increase in intensity and bandwidth when two CMEs interact in the interplanetary medium. The duration of the enhancement is consistent with the time a fast shock would take to transit through the preceding CME. The interaction seem to happen when a slow CME is followed by a fast CME from the same source region on the Sun. This discovery has important implications to the prediction of space weather using halo CMEs.

Lara and Gopalswamy are studying the near-surface manifestations of the 1998 April 29 CME which resulted in a complex interplanetary ejecta observed at 1 AU by Wind spacecraft. They found at least three smaller events preceding the major event. Interestingly, the three minor events involved mass ejection, including filament material. This has the interesting prospect of explaining the complex nature of the ejecta at 1 AU: Cool material has been found over the entire ejecta, not exclusively in the rear end as one would expect if a single CME had propagated to 1 AU. This may be a clear example of ‘‘CME cannibalism’’ proposed by Gopalswamy *et al.*

Yashiro, Gopalswamy and Sato (GSFC) examined the ‘‘Bastille-Day’’ flare (X-class flare of 2000 July 14 at 10:00 UT) in detail using Yohkoh and SOHO observations. The event was characterized by the ejection of an X-ray plasmoid from the eastern part of flaring region at 10:24 UT (around the peak of soft X-ray emission). Around this time, a hard X-ray burst was observed by the Yohkoh/HXT during 10:24-10:28 UT. The hard X-ray burst shows a very hard spectrum (Ratio of M1 and M2 band is 0.7), suggesting that a large number of electrons were accelerated to very high energies. The ejecta was also observed in EUV at 10:36 UT to the south east direction. The main flare loop developed to the northeast direction. In the SXT images, the magnetic shear was found to decrease with time. The hard X-ray images show that the foot-point sources show the ribbon structure, normally seen in H-alpha.

The Center for Solar Physics and Space Weather (CSPSW) has developed a data center to enable the increase of science return from a number of NASA space missions that acquire data on solar-terrestrial physics. The data center, known as CDAW data center (http://cdaw.gsfc.nasa.gov) provides preprocessed data in the form of images and movies to study solar eruptive events.

4 PLANETARY SCIENCES

4.1 Planetary Astronomy

Krasnopolsky and Cruikshank (NASA Ames) developed photochemical models for Pluto’s atmosphere. They proved that Pluto’s atmosphere is hydrodynamically escaping even for very small abundances of CH_4. Their models are the first photochemical models for a hydrodynamically escaping atmosphere. They made some adjustments in the basic continuity equation and in the boundary conditions to account for hydrodynamic flow in the atmosphere. They modeled the photochemistry for 44 neutral and 23 ion species in the atmosphere by solving a set of 67 second-order differential equations. Because of the high methane mixing ratio, Pluto’s photochemistry is more similar to that of Titan than that of Triton. The most abundant photochemical products are C_2H_2, C_4H_2, HCN, H_2, C_2H_4, HC_3N, and C_2H_6. These products almost completely absorb solar photons with $\lambda <$ 185 nm, therefore significantly increasing the number of dissociation events in the atmosphere. Photochemical losses of the parent species N_2, CH_4, and CO are much smaller than their escape. Precipitation and escape rates were calculated for all species. The structure and composition of Pluto’s ionosphere were also calculated. Some of the photochemical products might be detected using the technique of UV solar occultation spectroscopy from a spacecraft flyby. The models provide some clues for understanding Pluto’s evolution.

Krasnopolsky and Bjoraker (NASA GSFC) observed the O_2 dayglow at 1.27 μm on Mars with a long-slit cryogenic echelle spectrograph (CSHELL at the NASA Infrared Telescope Facility) having a resolving power of 40,000. The observations resulted in a map of the O_2 dayglow which extends from 10:00 to 16:45 in local time and from 45degS to 75degN. The O_2 dayglow is formed by photolysis of high-altitude ozone, and this dayglow is the best tracer of seasonal variations in photochemistry at low and middle latitudes. Their observations show that O_2 dayglow can be mapped with existing ground-based instruments. The measurements are used to study latitudinal, diurnal, and local variations in the dayglow intensity. The observed dayglow intensities are smaller than those calculated using the existing model by a factor of 3. The observation confirms the anticorrelation between ozone and water vapor observed from the Viking orbiters at midsummer. Coupled with the Mars Global Surveyor Thermal Emission Spectrometer (MGS/TES) observations of temperature, dust, and water vapor, the O_2 dayglow measurements comprise a good database to study Mars’ photochemistry and dynamics.

Krasnopolsky proved that strong fractionation of deuterium in photolysis of H_2O and above hygropause reduce the production of HD relative to H_2 on Mars by a factor of 3. The existing model for deuterium fractionation in chemical reactions on Mars may agree with the observed deuterium abundance if the eddy diffusion coefficient does not depend on solar activity (model 2). The Mariner 9 observations show very low variability of atomic oxygen with solar activity and require eddy diffusion to be proportional to solar activity (model 1). The fractionation factor for escape of hydrogen isotopes is equal to 0.016 and 0.16 for models 1 and 2. These values have been averaged over the solar cycle. The three-reservoir model for hydrogen isotope fractionation suggested by Krasnopolsky involves a reservoir composed primarily of water ice in the polar caps that isotopically interacts with the atmosphere. Assuming that water ice is half of the total volume of the polar caps and the polar layered deposits, the total loss of water from Mars is equal to a global layer of 65 and 160 m thick for models 1 and 2, respectively. Along with thermal and nonthermal escape, these values may include the loss of water by oxidation of regolith, if the released hydrogen escaped with isotopic fractionation. Though the solar wind α-particles are the main source of He on Mars, capture of the solar-wind H^+ and D^+ ions by Mars has a negligible effect on the thermospheric abundances of H and D. Improved observations of minor components in Mars’ thermosphere may resolve the problem of eddy diffusion at various solar activity and help choose between the models.

4.2 Cometary Studies

Krasnopolsky, Mumma (NASA GSFC), and Abbott (CEA) observed comet Hale-Bopp postperihelion in November 1997 using Extreme Ultraviolet Explorer (EUVE) and revealed soft X-ray emission from that comet. They also analyzed observations of three comets from the EUVE archive and detected soft x-rays from comet Borrelly and established upper limits for x-rays from two other comets. This work doubled the number of comet observations in their EUVE database, and soft X-ray emissions were detected in five of the eight observations. The measured X-ray luminosities are consistent with a $r^3/2Q_{gas}$ dependence and therefore favor a gas-related mechanism. The only viable candidate is the charge transfer mechanism. Using the observed X-ray luminosities as functions of aperture and assuming the presentation of the charge transfer spectrum by thermal bremsstrahlung or the power law, it is possible to make careful comparison of X-ray observations made with different instruments. While both EUVE pre- and postperihelion observations of Hale-Bopp demonstrate a regular behavior of x-rays from that comet, the outburst detected with the BeppoSAX and the nondetection with the ROSAT are puzzling. The authors suggest that the long-term EUVE observations reflect a mean X-ray emission while the comparatively short BeppoSax and ROSAT observations of comet Hale-Bopp could coincide with a maximum and a minimum in the heavy ion flux, respectively.

4.3 NEAR

Starr is an associate team member on the Near Earth Asteroid Rendezvous (NEAR) mission X-ray/Gamma-Ray Spectrometer (XGRS) experiment. He supports operations and has a lead role in data analysis. NEAR arrived at Eros 433 in February 2000, and will remain in orbit around the asteroid for 1 year. The XGRS will collect thousands of X-ray and gamma-ray spectra while in orbit around Eros. These observations will be used to obtain elemental composition maps of the surface of Eros. These mapped compositions will be compared to known meteorite compositions in order to determine whether Eros has the characteristics of any of these meteorite types. The maps will also be of importance in determining the nature of the formation and evolution of the Eros. The XGRS science team leader is Jacob Trombka at Goddard Space Flight Center. From May through August 2000 the NEAR spacecraft is in low orbit around Eros (35 - 50 km). During this time X-ray fluorescence has been detected from the surface of the asteroid for numerous solar flares and quiescent Sun conditions.

The NEAR XGRS has been included in the Inter-Planetary Network (IPN) for the detection of Gamma-Ray Bursts (GRB). The IPN now incorporates GRB information from the NEAR, Ulysses, Compton-GRO, GGS-Wind, and Konus spacecraft. The IPN has been able to determine the location of several GRBs closely enough and quickly enough to allow detection of optical and radio counterparts.

4.4 Lunar Data Analysis (Lunar Prospector Mission)

Starr is a Principal Investigator and Pamela Clark a Co-Investigator in the Lunar Data Analysis Program. Pamela Clark has used quantitative (sensor fusion) techniques to combined data from Clementine spectral reflectance and Apollo gamma ray spectra derived iron and titanium variation on the Moon. By using this approach, they have optimized the utility of measurements from each dataset. Gamma-ray measurements are used to provide bulk abundances for these two elements (based on calibration to bulk soil abundances). For spectral reflectance measurements, published Ti and Fe data (on the basis of soil bulk abundances and mineralogy) are recalibrated to represent Fe and Ti in minerals which absorb most efficiently at the selected wavelengths, namely Fe in pyroxene and Ti in ilmenite grains. They are developing this approach, and a classification matrix based on parameters derivable from near infrared, X-ray, and gamma-ray spectral measurements. Establishing this relationship between near infrared observations can also be useful in the interpretation of ground-based near infrared spectral measurements in terms of their geochemical, as well as mineralogical, significance.

4.5 MS2001

Starr is a Participating Scientist on the Mars Surveyor 2001 Gamma-Ray Spectrometer (GRS) experiment. This is a re-flight of the GRS that was part of the instrument complement on the Mars Observer mission that was lost in August 1993. The Mars Surveyor spacecraft will launch in April 2001, arrive at Mars nine months later, and spend two years in orbit. The principal investigator is William Boynton of the University of Arizona. The primary detector will be a large volume high purity Ge detector passively cooled to cryogenic temperatures. The gamma-ray spectrometer will detect radiation from the surface of the planet due to natural radioactivity and due to cosmic ray interactions in the Mars surface. In addition, there will be two neutron spectrometer systems sensitive to thermal, epi-thermal, and fast neutrons.

4.6 MESSENGER

Design and development for the Discovery MESSENGER mission has begun. The purpose of this mission is to collect global information on the surface, interior, exosphere and magnetosphere of Mercury. Launch will be in 2004. Two fly-bys of Mercury will be executed prior to orbital insertion in 2008. The principal investigator is S. Solomon of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. The lead institution for the spacecraft and mission operations will be the Johns Hopkins University Applied Physics Laboratory. Richard Starr will have a key role in the development, test, and calibration of the X-ray, gamma-ray, and neutron spectrometers that will fly on board the MESSENGER spacecraft.

5 INSTRUMENTAL DEVELOPMENT

5.1 Lightweight Optics

Chen, in collaboration with Bowers, Neff, Polidan (GSFC) and Romeo (CMA), continued the development of ultra lightweight mirrors for space astronomy. Significant accomplishments include the fabrication of a 0.5m replica with very good optical figure, using a precision mandrel loaned by the NASA Marshall Space Flight Center. Preliminary tests were also run on the temperature stability of composite replica mirrors when cooled to low temperatures with dry ice and liquid nitrogen. The mirrors showed excellent stability with very low CTE (coefficient of thermal expansion) and no detectable hysteresis. These results were presented to a meeting of the SPIE held in Munich, Germany. Two very lightweight telescopes were constructed using composite replica mirrors. The first unit is a Newtonian telescope with a 15 cm f/6 mirror. The second unit is a lensless Schmidt telescope with a 0.5m f/1.9 mirror.

Work continued on the developed of lightweight mirrors with active optics control. A computer controlled system was built to perform Hartmann tests, both normal and interferometric, and reduce the data. A number of active figure control mechanisms were fabricated using both force and moment actuation. A core reinforced 0.9m mirror weighing 4 kg was made to investigate the mechanical characteristics of a very stiff mirror. This mirror was loaned to colleagues at the USAF laboratory to demonstrate feasibility of holographically corrected telescope systems.

Chen, in collaboration with Oliversen and Kondo, continued to develop and refine a new concept lunar observatory. The concept combines low cost launchers, payload maximizing trajectories, radiation resistant detectors, advanced thermal insulation, high temperature superconductor bearing, very lightweight telescopes with active figure control, and nighttime operation without radioactive power sources. A robot was constructed to demonstrate autonomous and semi-autonomous deployment of a telescope on the Moon. A very lightweight 0.9m prototype telescope and truss structure was assembled. Investigations were made of the concept of using fiber optics to connect two telescopes as an interferometer to image extrasolar planets. The study was reported to a meeting of the IAU and a conference on Space Exploration sponsored by the American Society of Civil Engineers.

5.2 Fabry-Perot IR interferometer

Moran, along with Deming (GSFC), has designed and constructed a scanning Fabry-Perot interferometer, called ‘‘Athena,’’ for measurements of solar magnetic fields using an Mg I line in the mid-infrared (12 microns). The device uses a 2-stage scanning etalon system and a liquid helium cooled Si array detector under vacuum. The instrument is installed at the McMath-Pierce Telescope at The National Solar Observatory at Kitt Peak, Az., and will be used to create maps of solar vector magnetic fields. This instrument, the only one of its kind in the world, will allow unprecedented studies of upper photospheric fields, and when combined with lower altitude IR and visible magnetic field measurements, will contribute to three dimensional characterizations of the field. This information will be used to study solar flare magnetic field configurations for the purpose of developing predictive models, as well as flux tube expansion in the stratified solar atmosphere and magnetic wave phenomena on flux tubes.

5.3 Ground Based Coronagraph

St.Cyr is Principal Investigator for a NASA Headquarters Supporting Research and Technology grant to build a ground based coronagraph. The goal of this white light instrument is to measure electron temperature and speed in the low corona by a new method described recently by Reginald and Davila (2000, Solar Physics, in press). The project will produce a demonstration model and evaluate the feasibility for future spaceflight opportunities.

5.4 UMBRAS

Bruhweiler is working closely with Schultz, Hart, & Jordan (all at STScI/ CSC), and others at CUA and elsewhere to develop a free flying occulter called UMBRAS that would work in conjunction with a telescope place in a leading or following orbit to the earth. The present design makes use of existing technology and is an outgrowth of an original idea by Lyman Spitzer. The current UMBRAS design consists of a Solar-Powered Ion Driven Eclipsing Rover (SPIDER) attached to an occulter. Details and papers describing this proposed spacecraft can be found at http://www.stsci.edu/ jordan. The UMBRAS is designed to enable an astronomical observatory, either the NGST or other advance telescope, to image faint sources as close as 0.15‘‘ from target stars. Giant Jupiter-sized planets could be imaged as close as 5 AU from stars at a distance of 30 pc. A modification of this configuration may allow the imaging of even earth-like planets. This concept has been presented at several recent SPIE meetings and a more refined concept is being developed.

6 EDUCATIONAL OUTREACH & OTHER ACTIVITIES

SUNBEAMS (organizer: Carol Jo Crannell) began its third year with 14 teachers of 6th grade math and science from the District of Columbia Public Schools. The teachers each worked with a Goddard engineer or scientist for five weeks and developed lesson plans based on that work to take back to their schools in September. They will complete this cycle by bringing a class to Goddard for a full week of total immersion in math and science. SUNBEAMS has been cloned at the University of Minnesota and is being studied at another government laboratory.

The IACS strongly encourages the participation of graduate and undergraduate students as well as capable high school students in scientific research. IACS personnel directly supervising these students have been Bruhweiler, Chen, Crenshaw, Gopalswamy, Gabel and Kraemer. Bruhweiler and Gabel have regularly visited elementary and intermediate schools to lecture and assist teachers in astronomy and physics presentations and been judges for school science fairs. Bruhweiler has also served as a lecturer for local Catholic Schools. Gopalswamy gave a talk on ‘‘The New Sun’’ describing the effects of solar activity on humans at the Kiwanis International Club of North Bethesda.

Bruhweiler along with Yoji Kondo (NASA), Freeman Dyson (Princeton/IAS), Charles Sheffield (USL), and Sallie Baliunas (Harvard-Smithsonian) served as a co-organizer of the symposium on ‘‘Space Access and Utilization Beyond 2000,’’ held in Washington, D.C. in February 2000 at the annual General Assembly of the American Association for the Advancement of Science (AAAS). A monograph describing the proceedings is being prepared. Bruhweiler, Kondo and Sheffield will be the Editors. This meeting, with contributors from Russia, the European Space Agency, Japan's ISAS, as well as commerical interests, was held to explore the possibilities for commercial development of space.

Chen made presentations on lunar astronomy and lightweight telescopes to various organizations and public gatherings. Included are the Northern Virginia Astronomy Club (NOVAC) star party, NOVAC regular meeting, Central Region of the Astronomical League, Mason-Dixon Star Party, Stellafane, and others. He supervised summer student Alan Chen (Cornell U.) in making two computer animated video sequences.

In January 2000, Dr. Gibson helped coordinate a workshop for the Whole Sun Month analysis, and she is currently acting as an editor for the COSPAR-2000 edition of Advances in Space Research.

Gopalswamy and Green convened an international conference on Solar Eruptive Events during March 6-9, 2000. More than 100 scientists from all over the world attended. Papers presented in the conference will be published as a special section in the Journal of Geophysical Research (Space Physics).

Gopalswamy has been appointed again as a member of the organizing committee of IAU commission 10 for the period 2000-2003. He is the convener of the IAGA/IASPEI Division IV symposium on Active Sun, to be held in Hanoi, Vietnam, August 2001.

Gopalswamy was one of the editors (with T. Bastian and K. Shibasaki) of the book, Radio Physics from radio Observations, published by the Nobeyama radio Observatory, Japan.

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