FINAL REPORT (5/15/95 to 12/31/00)
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Report Period - This report covers the period 15 May 1995 to 31 Dec 2000. Previous annual reports were submitted to GSFC during the annual budgeting cycles.

Research Publications - A total of 22 publications resulted from this LTSA program, as listed in the attached bibliography.

Research Synopsis - This LTSA award funded my research on the origin of stellar X-ray emission and the validity of the solar-stellar analogy. This research broadly addresses the relevance of our current understanding of solar X-ray physics to the interpretation of X-ray emission from stars in general. During the past five years the emphasis has been on space-based X-ray observations of very young stars in star-forming regions (T Tauri stars and protostars), cool solar-like G stars, and evolved high-mass Wolf-Rayet (WR) stars. These observations were carried out primarily with the ASCA and ROSAT space-based observatories (and most recently with Chandra), supplemented by ground-based observations.

This research has focused on the identification of physical processes that are responsible for the high levels of X-ray emission seen in pre-main-sequence (PMS) stars, active cool stars, and WR stars. A related issue is how the X-ray emission of such stars changes over time, both on short timescales of days to years and on evolutionary timescales of millions of years. In the case of the Sun it is known that magnetic fields play a key role in the production of X-rays by confining the coronal plasma in loop-like structures where it is heated to temperatures of several million K. The extent to which the magnetically-confined corona interpretation can be applied to other X-ray emitting stars is the key issue that drives the research summarized here.

Pre-main Sequence Stars: X-ray observations have shown that the youngest stars with masses comparable to the Sun and ages of less than a few million years are strong X-ray emitters. Their X-ray emission is highly variable on timescales of hours to days and can reach X-ray luminosities in excess of $L_x \sim 10^{33}$ ergs s^{-1} during short-lived outbursts ("X-ray flares"). The intensity of these outbursts is truly phenomenal in comparison to the Sun, and can exceed the solar quiescent X-ray luminosity by 4 - 5 orders of magnitude. Amongst these young objects are the T Tauri stars, an early evolutionary stage which includes young stars surrounded by accretion disks (*classical* T Tauri stars, or cTTS) as well as active young stars for which little or no evidence of an accretion disk is seen (*weak-lined* T Tauri stars, or wTTS). Our own Sun is believed to have once passed through the T Tauri phase, and an understanding of the physical processes that drive the high levels of X-ray activity in T Tauri stars is thus directly relevant to our understanding of the young Sun and the physical conditions in the inner solar nebula where the terrestrial planets formed.

During this LTSA program, X-ray observations of both star-forming molecular clouds and individual pre-main-sequence (PMS) stars were carried out. These included ASCA observations of the Barnard 209 dark cloud in Taurus (Skinner et al. 1997), the Lynds 1517 dark cloud in Taurus-Auriga (Skinner & Walter 1998), and the young intermediate mass Herbig Ae star HD 104237 in

Chamaeleon (Skinner & Yamauchi 1996). Additional analysis of a large X-ray flare on the young infrared binary system ROX-31 was undertaken using ASCA archival data (Skinner 2000).

The above observations yielded a wealth of new information on the X-ray behaviour of young stars in nearby molecular clouds. First, it is now apparent that the onset of X-ray emission occurs very early in a star's lifetime, before the star becomes optically visible. This was demonstrated by the detection of the young IR source SSV L1517-11 in our study of the L1517 dark cloud. Numerous other optically invisible ptotostars have also been detected in X-rays in recent Chandra observations such as our deep 100 ksec observation of the ρ Oph cloud core (Daniel, Gagné, & Skinner, 2001, AAS-San Diego). Second, our observations show that PMS stars display a wide variety of time behaviour in their X-ray emission. PMS X-ray flares have now been detected which closely resemble compact solar flares, while other outbursts show mysterious time profiles that have so far not been successfully modeled using solar-like flare models. The intense ROX-31 flare analyzed by Skinner (2000) is a classic example of solar-like flare behaviour in a T Tauri system. In contrast, the long-duration slowly-decaying flare detected by ASCA in the wTTS binary V773 Tau (Skinner et al. 1997) has not yet been successfully modeled using slowly-evolving solar analogs such as two-ribbon flares. It thus appears that *some* of the X-ray flare activity in young PMS stars is clearly analogous to the solar case, whereas other outbursts (particularly long-duration flares that evolve slowly) have no clear solar analog. Third, our ASCA observations of PMS stars have provided important new information on the temperature (T) and emission measure (EM) distributions in the hot X-ray emitting outer atmospheres of T Tauri stars. Prior to ASCA, very little information on T and EM structure was available for TTS. Using ASCA spectra, we have been able to asses the (T,EM) structure during "quiet" periods when no large-amplitude variability is present, as well as track the changes that occur in the (T,EM) profile during large X-ray flares by making use of time-partitioned data (cf. the anlaysis of the V773 Tau flare by Skinner et al. 1997). We now know that outside of large flares, the X-ray emitting plasma of most T Tauri stars spans a range of temperatures from a few million K up to $\sim$20 - 30 million K. However, during large flares the temperature can increase to $\sim$100 million K in a matter of a few minutes. Time-resolved spectroscopy has shown that the X-ray temperature typically reaches its maximum very early during flares, even before the X-ray flux (or photon count rate) has peaked (cf. Skinner 2000). This is one manifestation of the so-called Neupert effect, which occurs in the Sun and has been discussed in the stellar context by Güdel, Benz, Schmitt, & Skinner (1996). Such rapid heating points clearly toward magnetic energy release as a key factor contributing to the strong X-ray variability detected in pre-main-sequence stars.

The Sun in Time: A long-term observing program was initiated during this LTSA research period with Dr. M. Güdel (PSI/ETH) and Dr. E. Guinan (Villanova) to assess how the Sun's X-ray properties change during its main-sequence lifetime. We have selected a sample of nine nearby G-type stars spanning an age range of 70 Myr (ZAMS) to $\sim$9 Byr. By using these stars as solar proxies, we can reconstruct the X-ray evolutionary history of the Sun's corona. Observations of this sample were carried out with ROSAT, ASCA, and the VLA (Güdel, Guinan, & Skinner 1997), and more detailed observations are now being conducted with Chandra and XMM-Newton.

The results so far are quite revealing, and provide insight into the Sun's long-term coronal evolution. The G-type stars in our sample show a multi-temperature coronal structure consisting of a cool plasma component at a few million K and a hotter component at $\sim$20 - 30 MK. The temperature and emission measure of the hotter component decrease rapidly with age, and the hot component contributes negligibly to the overall emission measure distribution at ages beyond $\sim$500 Myr. This trend very likely reflects the decreased efficiency of coronal heating that occurs as a solar-like star ages and spins down. On the basis of this study, we infer that a rapid softening of the Sun's X-ray emission occurred during its early lifetime (age $\leq$ 500 Myr). This change in the Sun's coronal properties may have had important implications for the development of planetary atmospheres in the inner nebula where the terrestrial planets formed.

Wolf-Rayet Stars: The standard paradigm for explaining X-ray emission in the Sun and other low-mass cool stars (spectral types ~F - M) involves magnetic plasma confinement. The observational evidence discussed above suggests that magnetic processes are important even during the earliest phases of stellar evolution. However, higher mass OB and Wolf-Rayet stars are thought to lack the outer convection zones believed to be necessary to sustain magnetic activity via a solar-like dynamo. Thus, the X-ray emission of massive stars has traditionally been attributed to mechanisms that do not involve magnetic fields. Currently, most theoretical models attribute the X-ray emission of *single* (non-binary) massive stars to shocks that are set up in the outer regions of their powerful winds by line-driven radiative instabilities. Such *radiative shock models* generally predict *soft* X-ray emission with characteristic temperatures $\leq$4 - 5 million K. This contrasts sharply with the much higher X-ray temperatures of low-mass stars, which typically span ~4 - 30 million K. In the case of massive binary systems (such as O + O or WR + O systems), an additional X-ray production mechanism may be at work in the form of *colliding wind shocks*. Theoretical models predict that high-temperature shocks should form in the region between the two components of a massive binary where their powerful winds collide. The temperature of the X-ray emitting plasma in such colliding wind shocks is a function of the wind velocity and is predicted to reach several keV ($\geq$10 million K) for typical wind velocities encountered in O and WR stars. Our X-ray observations have clearly confirmed the presence of such hotter plasma in several WR + O binaries.

Until quite recently, X-ray emission models for massive OB and WR stars had not been rigorously constrained by observations. However, several ASCA spectra of WR + O systems were obtained as part of this LTSA research program, and this work is now continuing with Chandra and XMM-Newton. Very recent observations, including high-resolution grating spectra with Chandra and XMM, are providing major challenges to theoretical models of wind shocks.

On the observational side, the most significant progress made in this LTSA program for massive stars was related to ASCA X-ray spectroscopy of massive binary systems. In several cases, we obtained the first usable X-ray spectra of WR + O binaries. Their intrinsic X-ray emission is generally brighter than that of single massive stars, and they are thus more favorable targets for obtaining good quality spectra in a limited amount of observing time. In contrast, X-ray spectroscopy of single massive O and WR stars is still primarily *terra incognita*. The large effective area of XMM-Newton is coming to the rescue here, and we are now just beginning to obtain good quality spectra of single WR stars. An XMM-Newton observation of the single WR star WR 110 was recently completed on 22 March 01 (PI: S. Skinner). It is absolutely essential to understand the X-ray behaviour of single O and WR stars before attempting to analyze the more complex emission of O + O or WR + O binary systems. This is necessary since the X-ray emission of binaries may include X-ray contributions from the individual stars, as well as a colliding wind shock contribution originating between the two stars. These separate contributions cannot in general be spatially decoupled in spectroscopic binary observations, where one usually only detects a single point source whose emission is the superimposed contribution of the stars themselves and the CW shock. An important exception here is the WR + O system WR 147, which we have observed simultaneously with ASCA and the VLA (Skinner et al. 1999), and which we also recently observed with Chandra's HRC (PI: J. Pittard, co-I: S. Skinner).

We acquired two ASCA spectra of the closest WR + O binary system known, γ^2 Velorum (d =

258 pc) in May 1994 (Stevens et al. 1996). This binary is one of the best candidates for colliding wind (CW) shock emission, and shows orbitally-phased changes in its X-ray absorption during the 78 day orbit. Such changes are anticipated from CW shock binaries with high inclination orbits since the X-rays originating in the shock region between the two stars are alternatively absorbed by the chemically-enriched WR wind and then by the less massive O star wind. The ASCA spectra showed rapid changes in the absorption as the O star passed in front of the WR star, and provided a definitive detection of plasma at kT $\sim$ 1 keV ($\sim$10 million K). This temperature is considerably hotter than can be explained via radiative shocks in the winds of the individual stars, and thus implicates a CW shock. We were indeed able to reproduce the ASCA spectra using hydrodynamic CW shock models. However, the rather modest spectral resolution of ASCA did not place stringent constraints on the hydrodynamic models. We have now obtained higher resolution Chandra grating spectra of γ^2 Velorum (Skinner et al. 2001, in prep.). These new spectra confirm the hotter plasma detected by ASCA. However, the Chandra spectra also raise some interesting new questions, since no line Doppler shifts were detected down to very stringent limits of a few mÅ . The lack of Doppler signatures of high-speed bulk flows is surprising in the context of shock models and the high wind velocities of $\sim$1500 - 2400 km s^{-1} that characterize the γ^2 Vel system.

During this LTSA program, we obtained the first simultaneous X-ray/radio observations of a massive WR + O binary. Our target was WR 147 (WN8 + O8-9), which was observed simultaneously with ASCA and the VLA (Skinner et al. 1999). This system is of interest since it emits strong X-rays as well as *nonthermal* radio emission. The ASCA spectra were sussessfully modeled using hydrodynamic CW shock simulations. The VLA was able to resolve the radio emission into two separate components (separation = $0.''6$), one of which is a thermal wind source and the other being nonthermal. It has previously been suggested that the nonthermal emission originates in the CW shock region, perhaps from relativistic electrons that are accelerated via the Fermi mechanism. However, our VLA data show that the observed radio spectral energy distribution drops off much more steeply at high frequencies than predicted for Fermi-accelerated electrons. It is thus apparent that the Fermi-acceleration interpretation for nonthermal radio emission in this WR + O binary will need to be modified.

Analysis of ASCA data for another candidate colliding wind system, V444 Cygni (WN5 + O6) was completed and the results were published in ApJ in January 1999 (Maeda et al. 1999). The ASCA light curves and spectra show variability in both the absorption column density and emergent X-ray luminosity with orbital phase. Maximum absorption occurs when the WN5 star is viewed in front of the O star, and the luminosity of the hard X-ray component is at a minimum when the O star is in front. These results provide support for the presence of an X-ray emitting colliding wind shock region between the two stars.

A detailed analysis of a set of ASCA archive spectra of the CW candidate binary system WR 140 (WC7 + O4-5) was undertaken by Zhekov & Skinner (2000). These spectra spanned half of the 7.9 year orbit, covering phases near periastron and near apastron. Variable X-ray absorption was seen, as expected for a CW shock. The spectra were reproduced using self-consistent hydrodynamic CW shock calculations. However, the observed spectra showed excess absorption above what was predicted by the models for the combined constributions of the stellar winds and interstellar medium. The origin of this apparent excess absorption is not yet known, but may involve non-spherical distributions of matter near the star. WR 140 is scheduled to be observed by XMM-Newton during its first observing cycle (PI: Y. Maeda, co-I: S. Skinner).

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