

Final Report for LTSA Program NAGW-4529:

7N-92-CR  
068472

**THE FUNDAMENTAL PHYSICAL PROCESSES  
PRODUCING AND CONTROLLING  
STELLAR CORONAL/TRANSITION-REGION/CHROMOSPHERIC  
ACTIVITY AND STRUCTURE**

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Our LTSA grant supports a long-term collaborative investigation of stellar activity. The project involves current NASA spacecraft and supporting ground-based telescopes, will make use of future missions, and utilizes the extensive archives of *IUE*, *ROSAT*, *HST*, and *EUVE*. Our interests include observational work (with a nonnegligible groundbased component); specialized processing techniques for imaging and spectral data; and semiempirical modeling, ranging from optically-thin emission measure studies to simulations of optically-thick resonance lines. Collaborations with our cool-star colleagues here in Boulder (at JILA and the High Altitude Observatory) provide access to even broader expertise, particularly on the solar corona, convection, and magnetohydrodynamic phenomena (including "dynamo" theories).

The broad-brush themes of our investigation include:

- (a) Where do Coronae Occur in the Hertzsprung–Russell Diagram?
- (b) The Winds of Coronal Stars: Hot, Cool, or Both?
- (c) Age, Activity, Rotation Relations.
- (d) Atmospheric Inhomogeneities.
- (e) Heating Mechanisms, Subcoronal Flows, & Flares.

Our observational tack has been to:

- Map the global properties of chromospheres and coronae in the H–R diagram.
- Conduct detailed studies of key objects.

**Final Report for FY97 grant period**

Over the past year, we have completed a number of major projects, and have taken advantage of several new opportunities to further the goals of our LTSA effort.

**Sleuthing the dynamo; Evolution of the Solar ionizing flux.** We completed a major study of *HST*/*FOS* and *ROSAT* measurements of solar-type stars from young galactic clusters. We derived rotation-activity relations for coronal X-rays ( $10^6$ – $10^7$  K) and subcoronal C IV ( $10^5$  K), and used solar magnetic loop models to show how the nonlinear flux-flux correlation diagrams arise (mostly from an increase in the mean coronal temperature with increasing activity). That work led into a study of the history of the solar ionizing flux, which is relevant to solar-induced erosion of the primitive Martian atmosphere (and bears on the question of the possible early development of life on that planet). In connection with the *FOS* project, new observations of three key cluster dwarfs have been obtained very recently by *GHR*S (in the G140L mode which does not suffer the severe scattered light problems of *FOS*, but which was not available in Cycles 2 and 3). The new observations were discussed at a recent meeting in Flagstaff Arizona concerning "Solar Analogs."

**Hertzsprung gap and Clump giants.** We also completed an extensive study of *HST*/GHRS, *EUVE*, *IUE*, and *ROSAT* measurements of moderate mass giants evolving through the Hertzsprung gap on their way ultimately to the post helium-flash “Clump.” Our objective was to understand the origin of the curious “X-ray deficiency” that characterizes the fast-rotating F–G0 giants. We developed a scenario—involving the properties of very long magnetic loops—to describe possible diversions of what normally would be coronal heating into other forms (primarily subcoronal emissions like C IV). We then speculated that the long loops, themselves, might represent a relic dipolar magnetosphere remaining from the MS phase (when the stars were A- or B-type dwarfs), which had not yet been disrupted by deep convection. We view that scenario—if correct—as a major breakthrough in our understanding of the evolution of magnetic activity on the moderate mass giants. The results of our project have led to successful proposals (*EUVE*, *HST*, *ASCA*) to observe other stars with shallow convective envelopes (e.g., the F supergiant Canopus) and stars at the critical evolutionary phase where deep convection first is able to disrupt the fossil magnetosphere (e.g., the G1 giant HR 9024). The paper will be published in the 20 March 1998 issue of ApJ.

**SUMER trans-limb spectroscopy; and the solar-stellar connection.** An important component of our original LTSA proposal was to pursue the “solar-stellar” connection using the ultraviolet spectrometers on *SOHO* when they became available to the general community. We were able to realize that goal in the fall of 1996 when one of us (TRA) served as a “weekly planning scientist” for the SUMER team. At the time, the azimuth control system (that steers the SUMER telescope in the East/West direction) had developed problems, and the spectrograph slit was commanded to the central meridian as a precautionary measure. Motions in elevation (i.e., North/South) were still possible. Nevertheless, many of the scheduled programs relied upon the E/W rastering capability of SUMER, and had to be modified or cancelled. The reduced pointing ability of SUMER thus opened up a considerable amount of observing time during the week that TRA was on duty, and allowed the execution a diverse range of observing sequences to study: the trans-limb emission spectrum, for determining the radial extension of the chromosphere, transition zone, and corona; chromospheric dynamics, through high-temporal resolution measurements of spectral diagnostics including emission lines of various excitation, and continuum bands; and center-to-limb measurements of key spectral regions commonly used in stellar work with *HST*/GHRS (and soon with STIS). These extensive data sets will provide the basis for a number of publications, and new perspectives on the Sun and the solar-stellar connection. In May 1997, we obtained further *SOHO* data during our second planning week. We discussed some preliminary results of the translimb work at the Solar Physics Division meeting of the AAS in Bozeman Montana in June 1997, again at the IAU General Assembly in Kyoto Japan in August, and once more in an invited review at a solar workshop at Sac Peak Observatory (New Mexico) in September.

**Far-UV spectroscopy of red giant stars.** We have obtained GHRS observations of low-activity red giant stars with *HST*/GHRS: detailed spectroscopy of Arcturus in Cycle 5, and low-res G140L spectra of 3 K giants in Cycle 6. Although the Arcturus observations technically failed—the star was outside of the small aperture for the bulk of the observations due to an acquisition error—some very useful data were obtained, including a medium-res spectrum of the crucial Si IV  $\lambda 1400$  interval. The latter spectrum shows very clearly the fluoresced bands of the carbon monoxide 4th-positive system, some of which are coincident with Si IV itself (the high-excitation line is an important proxy for coronal-temperature material). The recent Cycle 6 low-res observations of the other three K giants have been completed, and analysis is underway. Preliminary results were described at the January AAS meeting in Toronto. We have detected the coronal proxies Si IV and C IV in all of the objects, albeit at low flux levels. The implication is that magnetic activity continues in even the oldest and slowest rotating late-type stars (at the opposite end of the activity spectrum from the young, fast-rotating dwarfs in the galactic clusters). We subsequently have discussed these results at the Cool

Stars 10 meeting in Cambridge (MA) in July 1997, and a paper on the subject was published in the 20 December 1997 ApJ.

**Multi-spectral studies of active binaries.** We have conducted (and will conduct) multi-spectral observations of active RS CVn binaries during Years 2 and 3. HR 1099 (K1 IV + G5 IV) was observed by *EUVE*, *XTE*, VLA, and AT in September 1996 and  $\sigma^2$  CrB (F6 V + G0 V) will be observed by *ASCA*, *XTE*, VLA, and MERLIN in March 1997. During September and October 1996 we obtained a total of 24 days of *EUVE* photometric coverage on HR 1099 which include two large flares (one lasting over 3 days) and four smaller flares.

**ASCA X-ray spectra.** We have used the *ASCA* satellite to record X-ray spectra of a number of late-type stars including the Hertzsprung gap giants 31 Com (G0 III), HR 9024 (G1 III), and Canopus ( $\alpha$  Car, F0 II). *ASCA* is sensitive to the hottest coronal material in these objects, and we have deduced emission-measure distributions to describe the coronal structure. We now are in the process of linking the empirical distributions to magnetic loop simulations in an effort to understand the underlying processes that give rise to the extraordinarily hot coronae of these thin-convection objects. We presented initial results of the recent observations (i.e., HR 9024) at the HEAD meeting in November 1997 (in Estes Park, Colorado). We will be working on a major paper concerning 31 Com and HR 9024 in the near future.

**Large-scale stellar coronal structure from radio data.** We have examined the role of large-scale coronal magnetic structures on stars implied by radio observations from the VLA, MERLIN, and AT. Ray et al. (1997) show that the polarized radio outbursts from the pre-main sequence star T Tau S prove that large-scale magnetic fields are present around such stars from the earliest stages of their evolution. Jones et al. (1996) model multifrequency radio observations of the RS CVn binary HR1099 and derive field strengths and emitting region dimensions as a function of activity state.

**IUE image processing.** We have provided copies of our *IUE* low-res and echelle processing codes to the ESA *IUE* center at Vilspa for evaluation purposes (with respect to the historical IUESIPS and the recently-developed NEWSIPS package). There are key questions concerning the linearity of the processed *IUE* images at low exposure levels, and the very different strategy used by our algorithms (generically called "TOM\_SIPS") for the photometric linearization step provides an important adjunct to the techniques adopted by the *IUE* Project itself.

**IUE 1996 AGN Watch.** We participated in last year's final major program conducted by the *IUE* satellite: a nearly continuous month-long campaign to study the AGN NGC 7469 in the 1150–1950 Å region. TRA was responsible for a major part of the data analysis, using the TOM\_SIPS linearization, extraction, and calibration procedures. The data set consisted of nearly 120 SWP-LO exposures, very uniform in exposure time, and good S/N in each frame. There are obvious changes in the AGN continuum and line strengths over the period, at a level higher than anticipated at the outset. These observations currently are being evaluated. At the same time, the results of an earlier AGN Watch (target NGC 4151) were published. Here, again, TRA (and students at Colorado) played a key role in the data processing.

**Eclipsing binaries.** Our investigations of stellar chromospheric and wind structure using eclipsing binaries has continued with additional *HST*/*GHR*S observations of  $\zeta$  Aur (K4 Ib + B5 V) and new observations of 32 Cyg (K4-5 I + B6-7 V) during Cycle 6. We expect to complete several major papers on this topic during the coming year that deal with the detailed investigation of atmospheric column densities, atmospheric inhomogeneities and density enhancements, chromospheric turbulence, and wind mechanisms.

LTSA-RELATED PUBLICATIONS 1996-97 [refereed journals, only]

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3. T. R. Ayres, 1997, Evolution of the Solar Ionizing Flux, *JGR Planets*, 101, 1641.
4. N. Piskunov, B. E. Wood, J. L. Linsky, R. C. Dempsey, and T. R. Ayres, 1997, Local Interstellar Medium Properties and Deuterium Abundances for the Lines of Sight toward HR 1099, 31 Comae, beta Ceti, and beta Cassiopeiae, *Astrophys. J.*, 474, 315.
5. T. P. Ray, T. W. B. Muxlow, D. J. Axon, A. Brown, D. Corcoran, J. Dyson, & R. Mundt, 1997, Large-scale Magnetic Fields in the Outflow from the Young Stellar Object T Tauri S, *Nature*, 385, 415.
6. B. E. Wood, J. L. Linsky, and T. R. Ayres, 1997, Evaluating Possible Heating Mechanisms Using the Transition Region Line Profiles of Late-Type Stars, *Astrophys. J.*, 478, 745.
7. T. R. Ayres, and D. Rabin, 1996, Observations of Solar Carbon Monoxide with an Imaging Infrared Spectrograph. I. Thermal Bifurcation Revisited, *Astrophys. J.*, 460, 1042.
8. T. R. Ayres, T. Simon, J. R. Stauffer, R. A. Stern, J. P. Pye, and A. Brown, 1996, Sleuthing the Dynamo: Hubble Space Telescope Faint Object Spectrograph Observations of Solar-Type Dwarfs in Young Galactic Clusters, *Astrophys. J.*, 473, 279.
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11. R. A. Edelson, 19 authors, T. R. Ayres, et al., 1996, Multiwavelength Observations of Short-Timescale Variability in NGC 4151. IV. Analysis of Multiwavelength Continuum Variability, *Astrophys. J.*, 470, 364
12. K. L. Jones, A. Brown, R. T. Stewart, & O. B. Slee, 1996, Evidence for Narrow Bandwidth Highly Polarized Radio Emission from the RS CVn Binary HR1099, *MNRAS*, 283, 1331.