FINAL TECHNICAL REPORT FOR NAG 5-1327

March 15, 1994

This is the final report for the grant NASA NAG 5-1327 "Ultraviolet Observations of Astronomical Sources," which ran for a total of three years, roughly between July 1, 1988 and February 14, 1993. During the first year of this grant, I worked at Indiana University and the grant was part of NAG 5-599; since October, 1989, I have been at Tennessee State University. This grant has supported my studies of archival IUE observations of ζ Aur binaries, cool stars that are paired with hot stars in binary systems. Such systems are important as a source of detailed knowledge about the structures of chromospheres and winds in cool giant and supergiant stars, since the hot star serves as a probe of many lines of sight through the cool supergiant star's outer atmosphere. By determining the physical conditions along many such lines of sight, a detailed two-dimensional map of the chromosphere and wind may be constructed. The grant grew out of my analysis of archival IUE observations of 31 Cyg (Eaton, J.A. 1988, ApJ, 333, 288 "The Atmospheric Eclipse of 31 Cygni in the Ultraviolet") in which I analyzed five epochs of an atmospheric eclipse that occurred in 1982. I fit the attenuation spectra of atmospheric eclipse throughout the ultraviolet ($\lambda\lambda$1175-1950 and $\lambda\lambda$2500-3100) with theoretically calculated spectra, thereby determining the physical properties of gas (mass column density of absorbers, temperature, and velocity spread) along each observed line of sight. Grant NAG 5-1327 allowed me to do a similar analysis for other such ζ Aur bianries and to construct theoretical models for the chromospheres of these stars based on my observations. Results derived from the grant are as follow:

1. My analysis of intrinsic lines observed in the total eclipses of ζ Aur, 31 Cyg, and 32 Cyg (Ref. 5 below) showed that the deep chromospheric structure of cool stars in these binaries is likely very similar to that in single K supergiants. Such lines as Al II] λ2669, C II] λ2326, and fluorescent Fe I and Fe II lines near 2840 Å have such low optical depths in cool stars' chromospheres that they cannot scatter an appreciable amount of light of the B star in a ζ Aur binary. Therefore, they must be emitted by the processes that are intrinsic to the chromosphere itself, either excitation by electron-ion collisions or by the radiation of very optically thick resonance lines. Since the ζ Aur binaries have intrinsic lines with the same intensity as in single stars, the chromospheres are very likely similar.

2. I made the first extensive use of Lyα, the resonance line of hydrogen, to determine mass column densities along lines of sight through chromospheres of ζ Aur binaries. This is an important advance, in that it determines whether the measurements based on Fe II can be reliable. Measurements of Fe II and other sharp-lined metals depend critically on the Doppler width (velocity spread along the line of sight) used (i.e., derived from the analysis), but Lyα strength does not depend on the velocity field. My Lyα measurements have shown that the measurements made with metals are reliable, or, conversely, that the metals are truly singly ionized and hydrogen neutral as expected from theoretical chromospheric models. Furthermore, these analyses imply that the theoretical atomic

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model used for calculating the strengths of wings of Lyα is valid for use with IUE data of ζ Aur binaries.

3. I analysed extensive archival IUE data of ζ Aur (Ref. 6) and 32 Cyg (Ref. 7). These measurements give precise values of physical properties throughout actual chromospheres of cool stars. These include the mass column density along lines of sight through the gas, which determine how density is distributed in the chromosphere, the excitation temperature of Fe II, which may be equivalent to kinetic temperature, the Doppler width characterizing absorption lines of metals, which measures the spread of radial velocity in the absorbing gas, and ionization of common metals (e.g., Fe, C, Si, S), which determines the local electron density in the gas.

Density distributions in both stars can be characterized by two structures (1) an inner exponential zone in which mass density drops about 2-3 orders of magnitude with a scale-height about 10 $R_\odot$ at the surface of the star and (2) a zone above it in which density drops much more slowly, as if part of a wind. Whether these two regions are the same structure or whether they are separate (like chromospheric loops and wind in our Sun) is not yet clear. In ζ Aur they appear possibly separate but in 32 Cyg they seem possibly the same structrue.

Excitation temperatures in the chromospheric gas rise with height from moderate values (~4500-5000) deep in the chromosphere to values above 10^4K high in the wind. The values in the deeper layers (structure no. 1 above) are quite similar to temperatures required in semi-empirical chromospheric models to give observed emission lines of single stars.

Doppler widths in these chromospheres are all within the range 15-25 km/s. This is problematic in that such values are decidedly supersonic. Such high values seem to be required by Alfven wind models to give enough momentum transfer to drive off the observed winds. However, supersonic random velocities have to be received somewhat skeptically, since they imply unmodeled physical processes. [I will take this opportunity to cheat by relating a result from more recent IUE observations of 31 Cyg neither gathered nor analyzed as part of my archival program. These further, much better observations show that supersonic turbulence need not obtain in the chromosphere, but that the differential expansion of the atmosphere can account for all the observed velocity structure of shell absorption lines.]

Ionization of the metals in chromospheres of ζ Aur binaries is increased by photoionization by the UV continuum of the B star. Ratios of neutral to singly ionized states of such metals as Fe, Mg, C, Si, and S are all near 10^{-4} in the parts of the chromospheres with enough neutrals to measure. In addition, there are lines of neutral N and O that may be used to chart hydrogen ionization in the chromosphere. Since the extra photoionization is balanced by n_e-dependent radiative+dielectonic recombination, the level of ionization may be used to infer a minimum electron density. These values of n_e tend to be in the range 10^8-10^9 cm^{-3}. Inasmuch as the total hydrogen density is comparable to these values, the gas seems to be clumped enough to concentrate the few electrons coming from partially ionized hydrogen into the large local densities of electron inferred. Such concentration may be consistent with strengths of the Balmer absorption lines in cool subergiants (including ζ Aur binaries), but the strengths of Balmer lines also depend critically on the theoretically uncertain transfer of Lyα.

4. I have calculated a series of theoretical models for chromospheres of ζ Aur binaries, the first such models. As discussed above, I determined very accurate temperatures, column densities, and turbulent velocities in the chromospheres of 31 Cyg, ζ Aur, and 32 Cyg from the IUE data, and I also applied wide variety of ionization ratios to determining electron density. In turn, I then reduced these values to a representative chromosphere, for which I have calculated the expected emission lines with the nonLTE program PANDORA. This let me add extra electrons at each height to simulate the clumping that seems apparent from the measurements of ionization equilibrium. The models were roughly in hydrostatic equilibrium, but a rather large turbulent velocity was used to extend them enough to fit the observations. I have calculated several sets of models as part of this analysis, (1) a chromosphere for ϵ Gem for comparison (a model for it exists in the literature), (2) a model for ζ Aur binaries without any clumping of the gas, (3) a model with rather extreme clumping to give $n_e = 0.3\text{-}3 \times 10^9$ cm^{-3} at all levels in the chromosphere, and (4) another such model with intermediate clumping. I reported results at two conferences, the Seventh Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun (Ref. 3), in Tucson in October, 1991, and at the Atlanta AAS meeting in January, 1992 (Ref. 4). Results of the calculations suggested that the derived chromospheres are too massive, that the total mass column densities derived from observations of these binaries are probably biased by a few atypically dense structures that happen to be observed occasionally. I have tried to remove the discrepancy by increasing the radii of the stars used in constructing the theoretical models to give lower densities in the model chromosphere, but this has only a minor effect on the total mass column density at the base of the chromosphere.

5. There are two minor archival studies of ζ Aur bianries which I started late in the course of this grant but which I have not yet finished: I have identified all the detectable emission lines observed during the total eclipse of 32 Cyg and compared them with similar, somewhat weaker spectra of ζ Aur and 31 Cyg. I calculated a rough theoretical emission line spectrum, assuming that the observed lines are scattered out of the continuum of the B star by gas of varying optical depth and letting photons scattered in strongly absorbing lines from low-lying levels branch into other lines to high-lying levels. This sort of analysis predicts most of the lines actually observed, but it predicts the wrong spectrum unless the absorbing lines are rather optically thick. A paper (with Deena Rembert, an undergraduate student at TSU) awaits a decision about how to present the theoretical interpretation. A second study, which I started under NAG 5-1327, is the analysis of eclipse observations of 22 Vul. I delayed this analysis because the data are inferior to those for ζ Aur, 31 Cyg, and 32 Cyg. I have a student, Felicia Shaw, analyzing the IUE observations in the same way I have for the other stars, and I used archival IUE data in a paper prepared for the Eighth Cambridge Workshop (Ref. 9). In addition, I have used archival data from IUE extensively in my recent analysis of 31 Cyg outside eclipse (Ref. 8), in which I studied changes of that star's wind with time.

6. As part of this grant, I have used archival IUE data for stars like the ζ Aur binaries in part of one other studies. I fitted shell spectra of TT Hya, an Algol binary, to determine the mass column density, turbulence, and temperature of gas in its accretion cloud. The analysis showed that the extremely broad lines formed in the accretion structure are broadened primarily not by turbulence but by some "macroturbulent" process, such as rapid rotation. A rotational velocity of 80 km/s was derived. This analysis has led to the first high-dispersion IUE observations of an Algol binary in total eclipse; it will be published eventually in a comprehensive paper.

7. Finally, there are benefits from this archival proposal that go beyond the results just discussed. I have calculated very many attenuation spectra for atmospheric eclipses that I have used for analyses of newly made observations of ζ Aur binaries such as AL Vel (Eaton, J.A. 1994, AJ, 107, 729 "A Deep Atmospheric Eclipse of AL Velorum") and 31 Cyg (Eaton, J.A., & Bell, C. 1994, AJ, submitted "The 1992/93 Atmospheric Eclipse of 31 Cyg"). These papers find evidence for extreme chromospheric variability that might represent magnetic activity in bright giants (AL Vel) and accomplish the most thorough analysis yet for an atmospheric eclipse (31 Cyg). Without the results from NAG 5-1327, these two important results would have been unlikely.

PUBLICATIONS USING ARCHIVAL IUE DATA SUPPORTED BY NAG 5-1327

1. Eaton, J. A. 1990, "Ultraviolet Extinction in Zeta-Aurigae Binaries at Low Resolution," at *Sixth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, ed. G. Wallerstein, (San Francisco; Astr. Soc. Pacific), p. 246.
2. Eaton, J. A. 1991, "Ultraviolet Light Curves of V535 Arae," *Ap. Space Sci.*, **186**, 7.
3. Eaton, J. A. 1991, "Calculated Chromospheres for Zeta Aurigae Stars," paper presented at the Seventh Cambridge Workshop on Cool Stars, Tucson, AZ, 9-12 Oct. 1991.
4. Eaton, J. A. 1991, "Models for Supergiants' Chromospheres Derived from Zeta Aur Binaries," *Bull. AAS*, **23**, 1386.
5. Eaton, J. A. 1992, "The intrinsic lines of ζ Aurigae binaries," *M.N.R.A.S.*, **258**, 473.
6. Eaton, J. A. 1993, "On the Chromospheric Structure of Zeta Aurigae," *Ap. J.*, **404**, 305.
7. Eaton, J. A. 1993, "On the Chromosphere of 32 Cygni," *A. J.*, **105**, 1525.
8. Eaton, J. A. 1993, "31 Cygni: The B Star and Wind," *A. J.*, **106**, 2081.
9. Eaton, J. A., Henry, G. W., and Seeds, M. A. 1993, "Geometry of the Binary System 22 Vul=QS Vul," at *Eighth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, ed. J.-P. Caillault (ASP; San Francisco), in press.

Respectfully Submitted,

Joel A. Eaton
Principal Investigator