Colliding Winds and Tomography of O-Type Binaries

SUMMARY OF RESEARCH - FINAL REPORT

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1. Project Summary

This grant was awarded in support of an observational study with the NASA *IUE* Observatory during the 15th episode (1992), and it subsequently also supported our continuing work in 16th (1994) and 18th (1995) episodes. The project involved the study of FUV spectra of massive spectroscopic binary systems containing hot stars of spectral type O. We applied a Doppler tomography algorithm to reconstruct the individual component UV spectra of stars in order to obtain improved estimates of the temperature, gravity, UV intensity ratio, and projected rotational velocity for stars in each system, and to make a preliminary survey for abundance anomalies through comparison with standard spectra. We also investigated the orbital phase-related variations in the UV stellar wind lines to probe the geometries of wind-wind collisions in these systems. The project directly supported two Ph.D. dissertations at Georgia State University (by Penny and Thaller), and we are grateful for this support. No inventions were made in the performance of this work. Detailed results are summarized in the abstracts listed in the following section.

2. Bibliography

- Gies, D. R., Mason, B. D., Hartkopf, W. I., McAlister, H. A., Frazin, R. A., Hahula, M. E., Penny, L. R., Thaller, M. L., Fullerton, A. W., and Shara, M. M. 1993, "Binary Star Orbits from Speckle Interferometry. V. A Combined Speckle/Spectroscopic Study of the O Star Binary 15 Monocerotis", *Astronomical Journal*, **106**, 2072-2080.

  We report on the discovery of a speckle binary companion to the O7 V((f)) star 15 Monocerotis. A study of published radial velocities in conjunction with new measurements from KPNO and IUE suggests that the star is also a spectroscopic binary with a period of 25 years and a large eccentricity. Thus, 15 Mon is the first O star to bridge the gap between the spectroscopic and visual separation regimes. We have used the star's membership in the cluster NGC 2264 together with the cluster distance to derive masses of 34 and 19 $M_{\odot}$ for the primary and secondary, respectively. Several of the He I line profiles display a broad shallow component which we associate with the secondary, and we estimate the secondary's classification to be O9.5 Vn. The new orbit leads to several important predictions that can be tested over the next few years.

- Bagnuolo, W. G., Jr., Gies, D. R., Hahula, M. E., Wiemker, R., and Wiggs, M. S. 1994, "Tomographic Separation of Composite Spectra. II. The Components of 29 UW Canis Majoris", *Astrophysical Journal*, **423**, 446-455.

  We have analyzed the UV photospheric lines of 29 CMa, a 4.39 day period, double-lined O-type spectroscopic binary. Archival data from *IUE* (28 spectra well distributed in orbital phase) were analyzed with several techniques. We find that the mass ratio is $q = 1.20 \pm 0.16$ (secondary more massive) based on three independent arguments. A tomography algorithm was used to produce the separate spectra of the two stars in six UV spectral regions. The M-K spectral classifications of the primary and secondary, O7.5-8 Iab and O9.7 Ib, respectively, were estimated through a comparison of UV line ratios with those in spectral standard stars. The flux ratio of the stars in the UV is 0.36 ± 0.07 (primary brighter). The primary has a strong P Cygni N IV λ 1718 feature, indicating a strong stellar wind. We also present tomographic reconstructions of visual spectral data in the range 4300 to 4950 Å, based on seven observations of differing orbital phases, which confirm the UV classifications, and show that the primary is an Of star. From the spectral classifications, we estimate the temperatures of the stars to be 33,750 K and 29,000 K for primary and secondary, respectively. We then fit visual and UV light curves and show that reasonably good fits can be obtained with these temperatures, a semi-contact configuration, an inclination of $74° \pm 2°$, and an intensity ratio $r < 0.5$.

- Thaller, M. L., Bagnuolo, W. G., Jr., Gies, D. R., and Penny, L. R. 1995, "Tomographic Separation of Composite Spectra. III. UV Detection of the Hot Companion of Phi Persei", *Astrophysical Journal*, **448**, 878-884.

  We have used archival *IUE* high dispersion UV spectra of the Be binary ϕ Per and published spectroscopic radial velocity curves to reconstruct the individual primary and secondary spectra using Doppler tomography. The primary's spectrum has rotationally broadened photospheric lines (consistent with a spectral type B0.5 III-Ve) and narrow "shell" lines formed in its circumstellar disk. The recovered secondary spectrum (which contributes only $\approx$ 12% of the UV flux) has a very different appearance, with strong emission in C IV λ1550 and many narrow, weak absorption lines (mainly Fe V) similar to those found in the spectra of hot O-type subdwarfs (in particular the sdO6 star HD 49798). These results strongly support Poeckert's (1981) model in which the secondary is the stripped-down core of a once massive star. Such objects could be the progenitors of unusual supernovae.

- Penny, L. R., Gies, D. R., and Bagnuolo, W. G. 1996, "Two-Dimensional Ultraviolet Spectral Typing of O-type Stars", *Astrophysical Journal*, **460**, 906-913.

  We present equivalent width measurements of ultraviolet photospheric lines that are useful as spectral type criteria; these include 23 lines of He II, C III, N III, N IV, O IV, Si III, Si IV, S V, Fe IV, and Fe V in *IUE* spectra of 67 O3 to B0 stars of all luminosity classes. Seven lines and two line ratios are particular ly sensitive to spectral type, and we show how the ultraviolet spectral typing diagnostics lead to types that are consistent with optical types. There are few luminosity sensitive photospheric lines in the ultraviolet but we find that the N IV λ1718 line does have a significant luminosity variation among most O subtypes. This criterion leads to ultraviolet classes that are approximately in agreement with optical luminosity classes. This scheme was developed in order to estimate the spectral types and luminosity classes of tomographically separated component spectra of O-type binary systems.

- Penny, L. R. 1996, "Projected Rotational Velocities of O-type Stars", *Astrophysical Journal*, **463**, 737-746.

  I present an homogeneous set of projected rotational velocities for 177 O-stars based upon *IUE* high dispersion spectra of the UV photospheric lines. The line widths are estimated by cross-correlating each spectrum with the spectrum of a narrow-lined O-star (HD 34078), and the widths of the cross-correlation functions are transformed to projected rotational velocity using a calibration based on the $V \sin i$ data of Conti & Ebbets (1977). The sample includes 120 stars in common with those of Conti & Ebbets plus 57 new targets. I identify 10 stars as potential new double-lined

spectroscopic binaries and 20 rapidly rotating stars as possible new line profile variables (displaying bumpy profiles associated with nonradial pulsation). There are few narrow-lined stars among the more massive and more evolved O stars which suggests that macroturbulent broadening is important in such objects. The fastest rotators are found among the lower mass O stars, which may reflect a loss of angular momentum through stellar winds among higher mass stars.

- Stickland, D. J., Lloyd, C., Penny, L. R., Gies, D. R., and Bagnuolo, W. G., Jr. 1996, "Spectroscopic Binary Orbits from Ultraviolet Radial Velocities. Paper 21: HD 152248", *The Observatory*, **116**, No. 1133, 226-230 (no abstract).

- Stickland, D. J., Lloyd, C., and Penny, L. R. 1997, "Spectroscopic Binary Orbits from Ultraviolet Radial Velocities. Paper 25: HD 152218", *The Observatory*, **117**, No. 1139, 213-217 (no abstract).

- Penny, L. R., Gies, D. R., & Bagnuolo, W. G., Jr. 1997, "Tomographic Separation of Composite Spectra. IV. The Physical Properties of the Massive Close Binary DH Cep", *Astrophysical Journal*, **483**, 439-448.

  We present the results of a Doppler tomographic reconstruction of the UV spectra of the double-lined, O-binary DH Cep based on observations made with the *International Ultraviolet Explorer* (*IUE*). We describe cross-correlation methods we use to obtain precise radial velocities, and we present a radial velocity curve based on combined optical and UV measurements. We also show how we use fits of the cross-correlation functions to estimate the UV flux ratio and projected rotational velocities. The individual component spectra are classified as O6 V + O7 V using UV criteria defined by Penny, Gies, & Bagnuolo (1996). We place the individual components in the theoretical Hertzsprung-Russell diagram using the distance modulus and reddening estimated for its home cluster, NGC 7380, and we find that the stars are larger than estimates from prior studies of the "ellipsoidal" light variations. We reconsider the ellipsoidal light curve and show that there is a range in acceptable stellar radii (as a function of orbital inclination). We discuss the constraints on inclination and system masses based on cluster distance modulus, presumed synchronous rotation, and on consistency with masses derived from evolutionary tracks (which involves the issue of the temperature calibration of O-stars). We find that primary and secondary masses of $39 - 50 M_{\odot}$ and $35 - 45 M_{\odot}$, respectively, satisfy all the constraints from spectroscopy, photometry, distance modulus, and single star evolutionary tracks.

- Gies, D. R. 1995, "Colliding Winds in O-type Binaries", in *IAU Symposium 163: Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution*, ed. K. A. van der Hucht, & P. M. Williams (Dordrecht: Kluwer Academic Publishers), 373-381.

In close binary systems of O-type stars, the individual stellar winds will collide between the stars to form shock fronts. The existence of the shock region can be established through observations of excess X-ray emission and orbital phase-related variations in UV wind features and optical emission lines. Here I report on work in progress on the orbital variations of the UV wind lines in a large sample of O-binaries that have been observed with the *International Ultraviolet Explorer Satellite.* In most of these binaries, the blue absorption trough of the P Cygni lines weakens when the strong wind component is behind its companion, in accordance with expectations for colliding winds. I describe how the radial velocity variations of the wind features differ from the orbital motions. Finally I discuss observations of Hα emission in these systems (with emphasis on Plaskett's star). Such optical emission lines act as a probe of high density regions in the winds.

- Gies, D. R. 1996, "Observations of Colliding Winds in O-type Binaries", in *Workshop on Colliding Wind Binaries*, ed. V. Niemela & N. Morrell, Revista Mexicana de Astronomía y Astrofísica - Serie de Conferencias, **5**, 31-37.

  Stellar winds will collide in a bow shock in close binary systems of O-type stars. The presence of this boundary will truncate the full spatial extent of the two individual winds, and thus the spectral lines formed in the wind will appear differently when viewed from different orientations. Here I discuss the orbital variations of the UV wind lines in a large sample of O-binaries that have been observed with the *International Ultraviolet Explorer Satellite (IUE).* High density regions in the wind (near the photospheres and bow shock) will produce optical emission lines, and I describe the Hα emission properties of several systems. The physical characteristics of the component stars can now be better estimated through Doppler tomography, a numerical method to extract the individual primary and secondary spectra.

- Penny, L. R., Bagnuolo, W. G., Jr., and Gies, D. R. 1994, "Doppler Tomography of O-type Binary Systems", in "Evolution of Massive Stars: A Confrontation between Theory and Observation", *Space Science Reviews*, **66**, 323-326.

  We have analyzed UV photospheric lines of seven O-type binaries, by means of cross-correlation and Doppler tomographic methods, with the goal of estimating the physical properties of the individual stars. These systems are HD 1337 (AO Cas), HD 47129 (Plaskett's star), HD 57060 (29 UW CMa), HD 37043 (Iota Ori), HD 215835 (DH Cep), HD 152218, and HD 152248. Mass ratios have been obtained primarily from, a cross-correlation technique, but also by comparing K_1 to $V \sin i$ (assuming synchronous rotation), and a goodness-of-fit technique which compares the reconstructed secondary spectrum (for a grid of assumed mass ratios)

to standard spectra. The tomographic techniques allow us to separate the spectra of the components. We then can estimate the individual spectral types and luminosity classes of the stars (and hence $T_{\rm eff}$ and $\log g$, respectively), the luminosity ratio, and projected rotational velocities.

We discuss the physical properties of these O-type binaries. These are some of the early results of a large scale project involving some 40 O-type binary systems which we will study using IUE and complementary ground-based data.

- Bagnuolo, W. G., Gies, D. R., & Penny, L. 1994, "Separation of Composite Spectra of O- Binaries: Physical Properties of Iota Orionis and 29 Canis Majoris", in "Interacting Binary Stars", Astronomical Society of the Pacific Conference Series, Vol. 56, ed. A. W. Shafter (San Francisco: ASP), 417-423 (no abstract).

- Penny. L. R., Gies, D. R., & Bagnuolo, W. G., Jr. 1996, "Tomographic Separation of UV Spectra in O-Type Binary Systems", in Wolf-Rayet Stars in the Framework of Stellar Evolution, Proceedings of the 33rd Liege International Astrophysical Colloquium, ed. J.-M. Vreux, A. Detal, D. Fraipont-Caro, E. Gosset, & G. Rauw (Liege: Univ. of Liege), 289-295.

  Knowledge about the individual components of O-type binaries is difficult to obtain because of the severe line blending present in their spectra. An important new method is Doppler tomography, an iterative scheme that uses a set of orbital phase distributed spectra and both radial velocity curves to reconstruct the individual component spectra (see Bagnuolo, Gies & Wiggs 1992). These individual spectra can then be analyzed to determine various physical properties of the stars. Here we present results of a program of Doppler tomography of O-binaries observed with the *International Ultraviolet Explorer* (*IUE*). We present results for six systems: DH Cep, HD 165052, HD 93403, HD 93205, HD 149404, and HD 152248. All are double-lined spectroscopic binaries with periods ranging from 2.1 to 15.1 days. These systems are used as tests of current theories for massive close binary evolution, and are compared with single star evolutionary tracks. Five of the six systems have already or are currently undergoing Case A Roche Lobe overflow (RLOF). The four stars which are currently experiencing RLOF appear overluminous. The two stars which have ceased RLOF now appear to lie on new evolutionary tracks corresponding to their new total mass. Also we find no observational evidence that necessitates the inclusion of mass transfer onto a mass gainer.

- Penny, L. R. 1996, "Tomographic Separation of Spectra of O-Type Binary Systems", Ph.D. dissertation, Georgia State University.

Knowledge about the individual components of O-type binaries is difficult to obtain because of the severe line blending present in their spectra. An important new method is Doppler tomography, an iterative scheme that uses a set of orbital phase distributed spectra and both radial velocity curves to reconstruct the individual component spectra (see Bagnuolo, Gies, & Wiggs 1992, ApJ, 385, 708). These individual spectra can then be analyzed to determine various physical properties of the stars. The spectral types and luminosity classes obtained provide indicators of the temperatures and gravities. The individual projected rotational velocities can be used to test for rotational synchronization of the orbit or rapid spin-up due to mass transfer. For stars that are cluster members, an estimate of the magnitude difference together with the combined absolute magnitude results in individual luminosity estimates. Finally, it is possible to search for abundance differences due to mass transfer or loss.

Here I present the first results of a program of Doppler tomography of O-binaries observed with the *International Ultraviolet Explorer Satellite (IUE)*. The use of *IUE* high dispersion spectra is optimal for O-type binaries because of the presence of many photospheric lines in the UV (high excitation lines which are relatively free from contamination from circumstellar emission often found in their optical spectra). I describe cross-correlation methods that use narrow-lined spectral templates to obtain precise radial velocities and orbital velocity curves which are used in the tomography algorithm. I also show how these cross-correlation results can be used to estimate projected rotational velocities and UV magnitude differences. I have identified new spectral classification criteria based on UV photospheric lines that are directly applicable to these O-binaries. I present results for six systems: HD 215835 (DH Cep), HD 165052, HD 93403, HD 93205, HD 149404, and HD 152248. All are double-lined spectroscopic binaries with periods ranging from 2.1 to 15.1 days. These systems are used as tests of current theories for massive close binary evolution.

- Thaller, M. L. 1997, "Colliding Winds in Massive Binary Systems", Ph.D. dissertation, Georgia State University.

  Stellar winds are a well-observed phenomenon, and in massive stars this process may result in significant mass-loss from the system with dramatic evolutionary ramifications. In close binary systems of massive stars, the individual stellar winds will collide and form a shock front between the stars. The existence of this shock can be established through orbital phase-related variations in UV wind features and optical emission lines. High density regions in the wind (near the photospheres and the shock region) will produce Hα and He I emission which can be used to map out the mass-flow structure of the system. The existence of a shock front between the stars may influence the balance of mass-loss versus mass-transfer in massive binary

evolution, as matter lost to one star due to Roche lobe overflow may hit the shock and be deflected before it can accrete onto the other star.

I report here the results of an all-sky, high-resolution spectroscopic survey of 37 massive binaries and identify which show evidence of excess emission. I obtained data in both the southern and northern hemispheres and I have also included spectra from two other groups of observers, Gies et al. and Kaper et al. For four systems, the detection of Hα emission is new to this survey. I compare my results with two independent surveys of massive stars and find that binaries show a higher incidence and intensity of emission when compared to single stars of similar spectral type. The exact phase of stellar evolution in which colliding winds become significant is uncertain, but my results suggest that one or both stars of a binary system must be evolved off the main sequence to produce measurable colliding wind effects.

Seven systems in my survey (plus four identified by earlier surveys), show significant phase-related variations in emission, and I identify these as likely colliding wind candidates. For three systems, HD 149404, HD 152248, and HD 163181, I present a simple model of the mass distribution and flow based on Hα, He I λ 6678, and in some cases, the UV resonance lines. HD 152248 and HD 163181 are eclipsing binaries, and I used Hipparcos light-curves to correct for changing continuum flux levels that may have complicated the detection of colliding winds. An argument can be made that all these systems contain a colliding wind bow shock, although more data will be needed to make a conclusive detection.