UV-Blue (CCD) and Historic (Photographic) Spectra of ε Aurigae—Summary

R. Elizabeth Griffin
Dominion Astrophysical Observatory, 5071 West Saanich Road, Victoria, BC V9E 2E7, Canada; Elizabeth.Griffin@nrc.gc.ca

Robert E. Stencel
Department of Physics and Astronomy, University of Denver, 2112 East Wesley Avenue, Denver, CO 80208; Robert.Stencel@du.edu

Received March 19, 2012; accepted March 27, 2012

Abstract While there are numerous "new spectroscopic studies" of ε Aurigae reported in this special edition of *JAAVSO*, the one summarized here is believed to be unique on two counts: it concentrates on the blue and near-UV spectral regions, and it incorporates historical spectra from the previous eclipses of 1983 and 1956. The more data that can be collated, across all wavelength and time base-lines, the more conclusive the final model of this baffling object is likely to be. A more lengthy paper that includes illustrations of the spectra is being prepared for publication elsewhere. This short contribution summarizes the effort that has so far gone into data acquisition and preparation, and the principal results that are now emerging.

1. Data: recent CCD spectra

We have observed and analysed ~150 new CCD spectra of ε Aurigae at blue and near-UV wavelengths, recorded during the 2010 eclipse with the coudé spectrograph of the Dominion Astrophysical Observatory (DAO) 1.2-m telescope. The wavelength span observable in one exposure is about 145 Å, so we targetted spectral regions of specific interest, and monitored just those as opportunity permitted. The great majority was centred near λ3950 Å so as to include the Ca II *H* and *K* lines and the nearby strong ground-state Fe I lines; somewhat less frequent monitoring was centred on Hδ and spanned the strong low-excitation Fe I lines between λ4045–4071 Å, and a comparable number of spectra were centered near the Mg II doublet at λ4481 Å, where a useful mixture of low- and high-excitation lines occurs. Some observations were also made in the red spectral region, near Hα. All the spectra were reduced in the world coordinate system by a semi-automatic pipeline, and were then extracted in steps of 0.01 Å and linearized to an apparent continuum height of 100%. If original S/N ratios were rather low, sequential spectra were co-added.

2. Data: historic photographic spectra

We digitized over 130 historic spectra of ε Aur from Mount Wilson (dating back to the 1930s) and from the DAO (dating from 1971) using the DAO's PDS microphotometer, resurrecting and adopting procedures that have stood the test of time. Spectrophotometric calibrations were determined by means of special exposures to a light source through apertures of known geometrical characteristics. Those spectra were also extracted in regular steps of 0.01 Å and linearized to the local stellar continuum. Many had very acceptable S/N ratios, though none quite as high as can be achieved with a modern CCD detector on a bright star. Nevertheless, these heritage data contribute uniquely to this study, by revealing which of the many line-profile changes have repeated at identical phases of past eclipses, thereby furnishing important constraints for a model of the structure and formation of the occulting disk. They could then be merged with the recent CCD ones so as to provide a more complete dataset, which we examined by ranging each spectral region with phase, within the wavelength spans defined by the CCD spectra.

3. Properties of the disk

We adopted the parameters of the radial-velocity orbit of Stefanik *et al.* (2010) ($P = 9896.0 \pm 1.6$ days, $K = 13.84 \pm 0.23$ kms^{-1}, T = HJD 2434723 ± 80), and aligned the spectra in the velocity rest-frame of the F star. The zero phase of that orbit solution corresponds to periastron, so photometric eclipse began close to phase 0.056 and ended close to phase 0.130. Mid-eclipse (secondary conjunction) was at phase 0.091.

Many authors—e.g., Struve (1956), Wright (1958), Hack (1962), Lambert and Sawyer (1986), and Ferluga and Mangiacapra (1991)—have drawn attention to curious line-profile changes, particularly during early ingress and late egress, often referring to them as "line doubling."

(a) The principal line-profile changes are the extra absorption components that become superimposed on ground-state and low-excitation lines. The new features are red-shifted during ingress and blue-shifted during egress, and are best seen in lines of Fe I on account of the latter's strength and number. The lines themselves do not actually "split," since the two distinct components originate in quite different regions of the system.

(b) Comparisons of the Fe I profiles at different times furnish limits to the phases (and hence on the geometry) when that "doubling" commenced and ceased. It is apparent that the occulting disk has a "tail" which trails much more extensively than does any material at its leading edge. Our spectra also demonstrated the existence of more rarefied material in the extremes of the "tail," not unlike that in a cool-star chromosphere.

(c) Comparisons of spectra of the same phases but different orbital cycles indicate that the structure of the disk is stable, at least on a time-scale of a century or so: the same "line-doubling" recurs at identical phases and its characteristics repeat quite precisely.

(d) Extra-narrow disk features in both ingress and egress suggest regions of exchange of material (between the disk and the supergiant) that are highly confined in both direction and velocity.

4. Instabilities in the F star

At all orbital phases the spectra of the system reveal more subtle line-profile changes: the absorption lines which presumably originate in the F-star photosphere (since they show no phase-related velocity changes) can weaken, or broaden, or strengthen a little. Dividing all spectra of a given region by one recorded far from eclipse accentuates the changes, and shows broad emission features that grow and fade at all phases on time-scales of days or weeks, with associated narrowing (or deepening) of the *K*-line wings resembling a rise (or fall) in T_{eff}. For the recent eclipse, there was some evidence of correlation between the growth of emission and the Cepheid-like pulsations of ~67 days' period (Kim 2008), but the recorded photometry had not been sufficiently plentiful in the past to investigate such correspondences in earlier years, nor are the available spectra adequate for a thorough investigation: a quarter-phase is only 17 days, and spectra must correspond to null or maximum—a requirement that is unlikely to be fulfilled given the eclectic nature of the archival data for a system of such long period.

5. The spectrum of the disk

The absorption of the disk itself can be isolated by dividing eclipse-phase spectra by one of the system far from eclipse. The procedure cannot be fully precise or absolute because of the small intrinsic variations in the system's spectrum referred to above; the disk spectrum also contributes to the system's one at all phases, though those contributions are small compared to the substantial absorption which the edges of the disk create during eclipse phases. The prime features that we thus isolate are the red-shifted (ingress) and blue-shifted (egress) absorption lines; they vanish during the phases of central eclipse. Their respective velocity displacements are surprisingly constant, and while both are considerably sharp the blue-shifted ones appear broader at phases which are actually beyond the end of photometric eclipse. It is therefore only at the leading and trailing edges of the disk that optically thin material is sufficiently concentrated to give rise to detectable absorption features. However, the presence of variable emission also in the system requires modelling before a quantitative assessment of the properties of that absorbing material can be made.

Qualitatively, the disk features are very similar to the absorption lines which arise in a cool-star chromosphere and which can be isolated during ingress or egress phases of an "atmospheric" eclipse in a ζ Aur system. The lines in ε Aur are ground-state or low-excitation transitions of easily-ionized elements like Ti I and Fe I, whereas there are no corresponding features in Mg II λ4481 Å, for example. As with a stellar chromosphere, the total absence of line wings, even for hydrogen lines, indicates a surface gravity, log *g*, < 1.

A comparison between the ingress and egress features of the disk shows that the disk is not symmetrical: its leading edge is more compressed than its trailing edge. Although the velocity shifts are largely constant, during the extreme end of the egress phases (phase ~0.125 onward) the blue-shift in velocity begins to decrease. Around the same time the sharpness of the features is particularly accentuated. Those observations suggest that we are seeing material which is flowing along a very confined path from the F star to the disk.

6. Transient absorption lines during egress

A few weak, narrow absorption lines appear only between phases 0.111 and 0.123 (or possibly later). They have a constant velocity offset that matches what is shown by the sharp egress features, and their appearances were repeated at identical phases in earlier orbital cycles. Most appear to be low-level lines of Fe I, though not all have yet been identified. The curiously tight restriction in phase suggests an enhanced absorbing mechanism which comes into play *only* during the second stage of egress; there is no counterpart during ingress. Their remarkable sharpness is probably limited by the resolution of the observations and is therefore only an upper limit; a measured half-width suggests an upper limit of ~9 kms.

7. Acknowledgements

We acknowledge the support of the HIA/DAO in granting observing time, when many spectra of the 2010 eclipse were obtained. We are also grateful to the DAO and to Mount Wilson Observatory for the loan of their photographic spectra of the system, and to the American Astronomical Society for a Small Research Grant to digitize them.

References

Ferluga, S., and Mangiacapra, D. 1991, *Astron. Astrophys.*, **243**, 230.
Hack, M. 1962, *Mem. Soc. Astron. Ital.*, **32**, 351.
Kim, H. 2008, *J. Astron. Space Sci.*, **25**, 1.
Lambert, D. L., and Sawyer, S. 1986, *Publ. Astron. Soc. Pacific*, **98**, 389.
Stefanik, R. P., Torres, G., Lovegrove, J., Pera, V. E., Latham, D. W., Zajac, J., and Mazeh, T. 2010, *Astron. J.*, **139**, 1254.
Struve, O. 1956, *Publ. Astron. Soc. Pacific*, **68**, 27.
Wright, K. O. 1958, *Astron. J.*, **63**, 312.