ζ Aurigae: Periodic Photoexcited Si I Emission

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Abstract.

We present periodic Si I line emission (3905 Å & 4102 Å) observed in the detached eclipsing binary system ζ Aurigae (K4 Ib & B5 V). Narrow periodic emission features are formed in a spatially-localized 'hot spot' near the B star's substellar point in the upper photosphere of the K supergiant owing to UV irradiation by the secondary. Since this flux illuminates only part of the primary's visible hemisphere at a given phase these lines provide us with spatial information on these objects. Examining the perturbation of the K supergiant as the B star approaches sheds light on the line formation mechanisms and atmospheric structures of both binary and single stars. From this information local properties can be determined, for example, the rotational velocity, the local (as opposed to disk-averaged) turbulence. Since the orbital parameters of the system are well determined the diagnostic power of these lines can be used to full effect. A qualitative analysis of the line emission yields good agreement with observation; a full radiative transfer solution, however, will allow quantitative measures of, for instance, the angle-intensity distribution of the line emission and enable detailed insight to be gleaned from this powerful and unique diagnostic.

1. Observations

Emission in Si I 3905 Å from ζ Aur was first detected in 1935, when mention was given in a footnote which Christie & Wilson added *in press* to their paper (Christie & Wilson 1935). It has since received no mention at all, until it was 're-discovered' by R.F. and R.E.M. Griffin at Calar Alto in 1988. Occurrences of the emission in other composite-spectrum binaries were also sought, and found definitely in two other systems (32 Cyg and HR 2030), but were not as prominent there as in ζ Aur, which is therefore the focus of this presentation.

Our database of observations was derived from about 100 high-dispersion coudé spectra of the λ3905 Å region in ζ Aur, and spans 50 years. Eight are photographic spectra from Mount Wilson Observatory, four (also photographic) are from Calar Alto, while the most recent are CCD spectra recorded at the Dominion Astrophysical Observatory, Canada. The latter set includes all the instances of null detections. All but some of the photographic spectra were recorded at dispersions near 2.2 Å/mm. In numerous cases spectra that were recorded at adjacent times were co-added to improve the S/N ratio, yielding a final data base of 71 spectra. Between them they cover some 18 cycles of the 972-day orbit of the star.

When an eclipse spectrum of the K supergiant is subtracted from the composite spectrum, the spectrum of the hot star (ζ Aur B) is revealed, together with any other features that were recorded in the composite spectrum but not seen in the total-eclipse. Emission at λ3905 Å can then be isolated cleanly, as it falls in a region of pure continuum in the hot star. Emission at λ4102 Å is also seen, but it appears in the redward wing of the Hδ absorption feature. It is therefore less useful for quantitative measurements, but its presence is valuable in confirming the identification of λ3905 Å as Si I. Those two emission features vary periodically during the orbit. We have sufficient observations of λ3905 Å in ζ Aur to conduct a detailed analysis of the Si I emission. Phase changes in the emission profile are presented Fig..1.

2. Modelling the Si I Emission

In assessing the line profiles we can see that:

1. The flux of the Si emission is phase dependent, being visible from the Earth when the face of the supergiant is illuminated by the B star.

2. The width of the emission profile (Doppler width $\sim$ 15 km/s) implies that the lines are formed deep in the atmosphere of the K supergiant, probably near the temperature minimum. The Doppler widths are above those given by **?** for the photosphere, <10 km/s, and below the chromospheric values measured by Schröder et al. (1990) & Eaton et al. (2008), $\sim 20-25$ km/s. The wind lines are typically $\sim$ 50 km/s and lines formed in the photosphere of the B-star are broadened rotationally, since vsin $i \approx$ 200 km/s for ζ Aur B. Neutral silicon is readily photoionized by the UV continuum of the hot companion shortward of the ground state ionization edge at λ1521 Å. Therefore, the presence of Si I in the K supergiant must necessarily be restricted to depths below which this ionizing radiation cannot penetrate: the upper photosphere.

These facts suggest that the emission in Si I λ3905 Å and λ4102 Å originates in the atmosphere of the K supergiant when it is irradiated by the ultraviolet flux of its hot companion; our analysis is based on this assumption.

We examined the possibility that the increase in flux may be due to reflection, but the inadequacy of this explanation can be demonstrated by recourse to the geometry of the system. Following Eddington (1926) we derive that the reflected flux should be of the order of 2%, insufficient to account for the observed increase (which amounts to 200 mA at its peak).

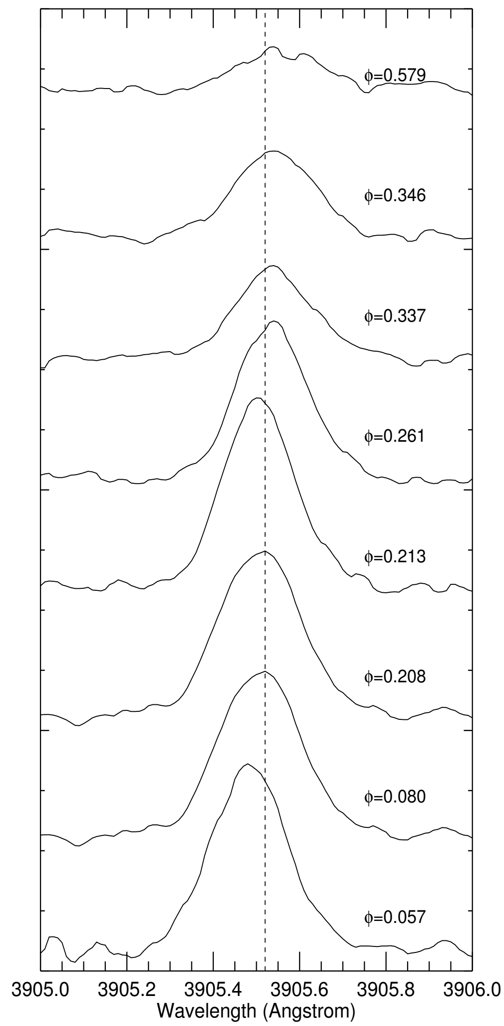

Figure .1: Line profiles of Si I $\lambda3905$ Å obtained at several different phases, ϕ, where ϕ is the fractional orbit elapsed from periastron. They are offset vertically for clarity. The phase dependency of the line can be clearly seen.

The emission in $\lambda3905$ Å and $\lambda4102$ Å must therefore be due to a line formation mechanism that channels the radiative energy effectively into specific wavelengths. We are led to the hypothesis that irradiation by the hot star causes photo-ionization and radiative recombination to Si I. The emission should, however, have the same phase variation as reflection, being dependent on the separation of the components and the amount of the visible K-star hemisphere being illuminated. In order to examine the phase variation we constructed a

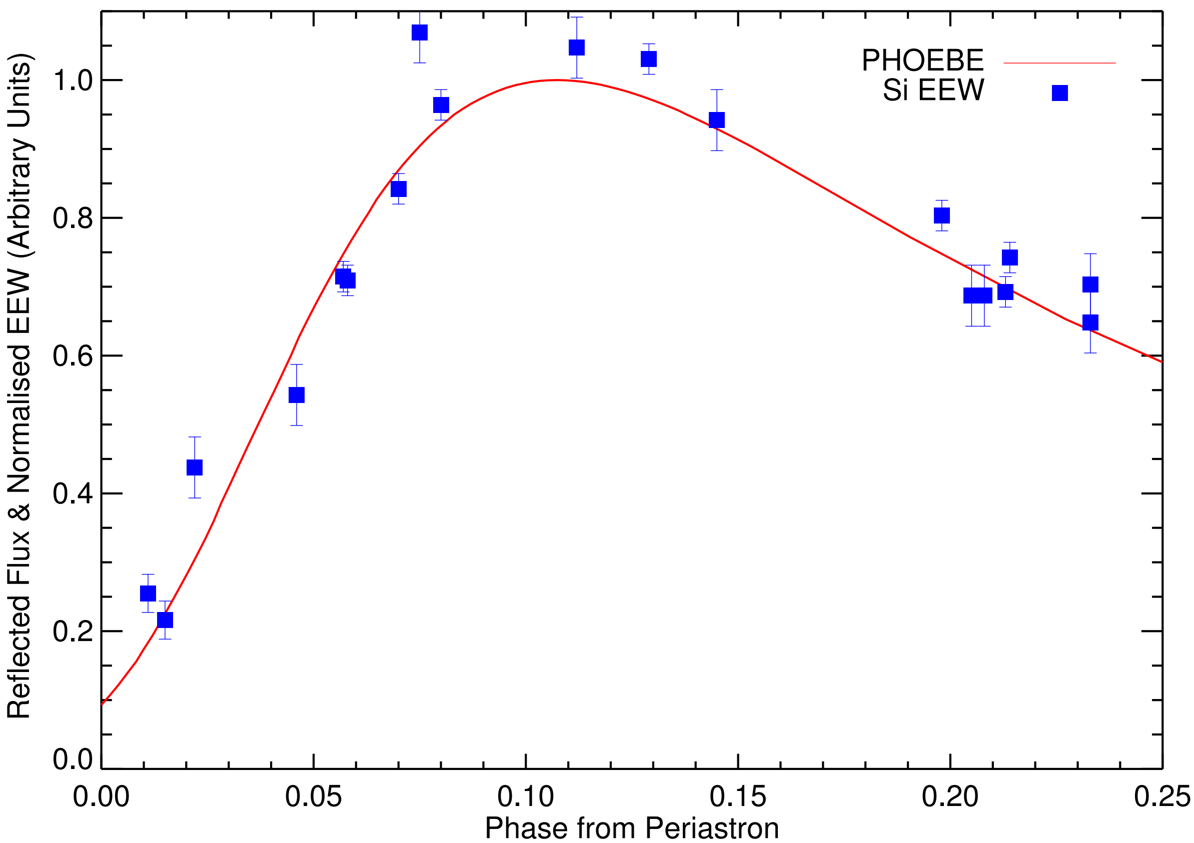

Figure .2: Si I λ3905 Å Emission Equivalent Width (EEW) as a function of phase for a period covering peak emission. The PHOEBE model over plotted provides a good match to the data for these phases.

model of the ζ Aur system using PHOEBE[1]. The system model was generated using the stellar parameters and orbital elements of Bennett et al. (1996) & Eaton et al. (2008).

The model then allows us to generate a light-curve taking account of reflection and tidal distortion of the K-star. It was used to examine the variation of reflection as a function of phase. The variation of reflected broadband flux can be seen in Fig. .2. The computed reflection curve is a good fit to the observed Si emission. There are no systematic discrepancies in the fit, as there would be if, for example, the 'hot spot' responsible for the Si emission lagged appreciably behind the substellar point. The similarity between the phase dependence of broadband reflection and the Si emission points to the conclusion that the phase variation of the Si emission, though not simply a reflection effect, can be explained in great part by reflection alone. There are, however, discrepancies between the reflection

[1] *http://www.phoebe-project.org/*

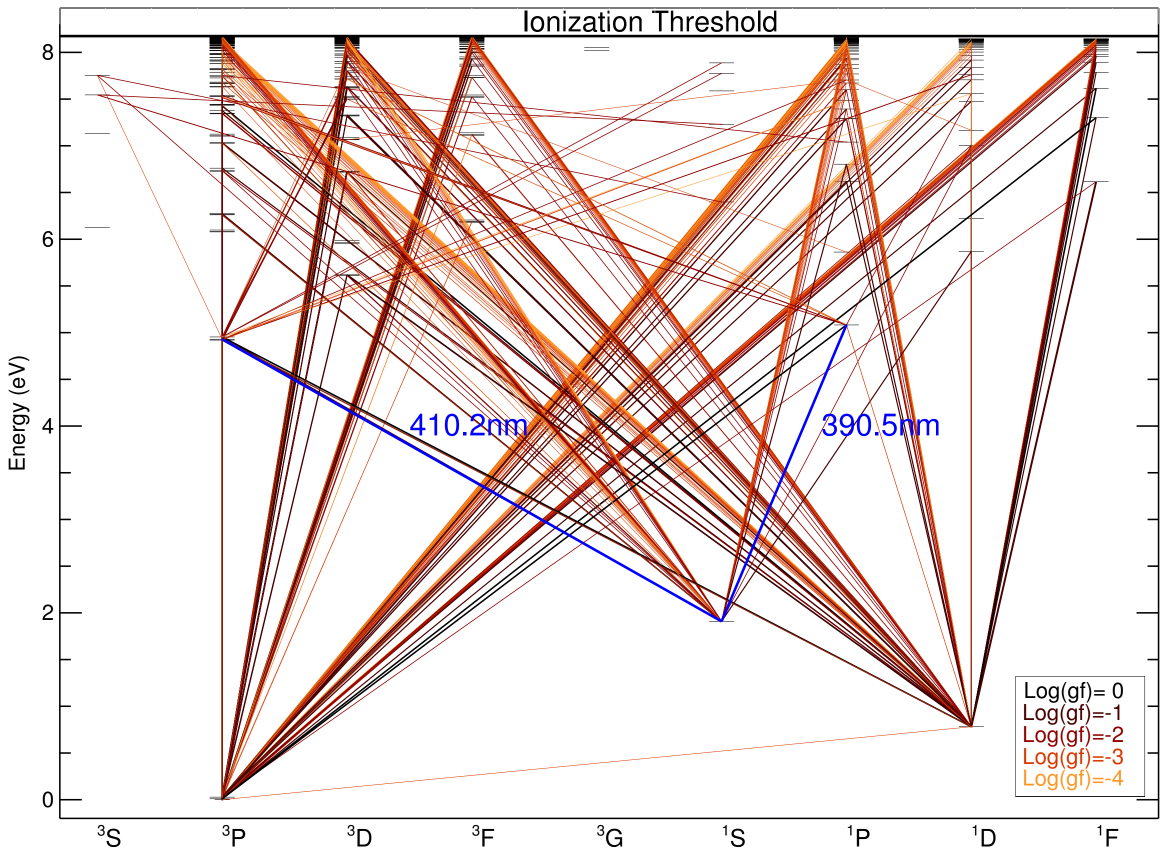

Figure .3: Si I Grotrian diagram. The thicker and darker lines have a higher $\log(gf)$. The λ3905 Å and λ4102 Å transitions of interest are highlighted in blue. The atom shown above will be used in the radiative transfer calculation.

curve and the observed emission, particularly $\phi = \sim 0.4$, which will require a model of the stellar atmosphere a radiative transfer solution to characterise fully.

3. Radiative Transfer Modelling

The next step in the analysis is to solve the full radiative transfer problem, modelling the Si I emission in the illuminated K supergiant atmosphere using the RH code (Uitenbroek 1989). We are constructing a semi-empirical atmospheric model of the K supergiant based on the previous work of Eaton (1993) & Schröder et al. (1988). The model can be further informed by comparison with high-resolution HST-GHRS data. Observations of the C II] λ2325 Å lines provide constraints on the electron density in the chromosphere.

Along with the atmospheric model we have constructed a detailed model of Si I, shown in Fig. .3. The model has ∼600 levels, and ∼2000 transitions. The energy levels are taken from NIST (Kramida et al. 2013) and the transitions from the Kurucz line lists (Kurucz R., Bell B. 1995)[2]. An atom of this size is required to account accurately for recombination of electrons to the upper levels. Once this recombination has taken place the electron will cascade through the levels before finally emitting a photon in one of the two observed lines.

A full radiative transfer solution will provide flux predictions as well as the angle dependence of the emission. It will also allow us to make estimates of the effect of the ionization change induced by the B star's radiation on the temperature structure of the K supergiant's chromosphere.

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References

Bennett, P. D., Harper, G. M., Brown, A., & Hummel, C. A. 1996, ApJ, 471, 454

Christie, W. H., & Wilson, O. C. 1935, ApJ, 81, 426

Eaton, J. A. 1993, ApJ, 404, 305

Eaton, J. A., Henry, G. W., & Odell, A. P. 2008, ApJ, 679, 1490

Eddington, A. S. 1926, MNRAS, 86, 320

Gray, D. F. 1976, Research supported by the National Research Council of Canada. New York, Wiley-Interscience, 1976. 484 p.,

Kramida, A. et al. 2013, NIST Atomic Spectra Database (version 5.1), [Online], National Institute of Standards and Technology

Kurucz R., Bell B., Atomic Line Data, Kurucz CD-ROM No. 23. Cambridge, Mass.: Smithsonian Astrophysical Observatory, 1995., 23

Schröder, K.-P., Reimers, D., Carpenter, K. G., & Brown, A. 1988, A&A, 202, 136

Schröder, K.-P., Griffin, R. E. M., & Griffin, R. F. 1990, A&A, 234, 299

Uitenbroek, H. 1989, A&A, 213, 360

[2] *http://kurucz.harvard.edu/*

Ilaria Pascucci and "The EUV Luminosity from Young Cool Stars: Implications for the Dispersal of Protoplanetary Material".