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Giants of Eclipse: The ζ Aurigae Stars and Other Binary Systems

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Cover illustration: Atmospheric-eclipse phases of a ζ Aurigae system. The small hot secondary is shining through different layers of the chromosphere of its cool-giant primary just before (or just after) phases of total eclipse.

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Dedicated posthumously to the leadership,
perseverance and scientific insight of
K.O. Wright, one-time Director of the
Dominion Astrophysical Observatory, and
himself a giant in eclipse spectroscopy of the
ζ *Aurigae stars*

Foreword

Although binary and multiple star systems make up about 60–70% of stars in the Galaxy, only about 0.5% are in systems that undergo eclipses; the requirement that the plane of a binary's orbit be aligned edge-on is sufficiently stringent (the more so when stellar separations are large) that such alignments are very unlikely. This is a serious limitation because eclipsing binaries play crucial roles in astrophysics by providing, among other things, fundamental measurements of stellar masses, radii, and luminosities. But among those rare eclipsing binaries are a few even rarer ones that offer crucial information on the structure and physical conditions of stellar atmospheres, interiors, and evolution that currently cannot be secured by any other means. In the case of the ζ Aurigae binaries (the subgroup highlighted here), the small, hot component serves as a beaming probe of the outer atmosphere, or chromosphere, of its much larger cool giant or supergiant companion just before and just after being eclipsed by that star. The favorable geometry offers a powerful laboratory that allows the physical properties of the cool star's chromosphere to be determined at varying distances from the stellar surface.

The primary source of information about these fascinating objects has for nearly half a century remained the review by K.O. Wright in *Vistas in Astronomy*, 1970. My own copy of that paper is well worn and dog-eared from persistent use over the years. It is a well-deserved testament; even though the interferometry, UV spectroscopy, sophisticated theory and modelling of stellar chromospheres, and asteroseismology of modern research were not available, or not at all developed, in Wright's time, it is amazing to appreciate how much had nevertheless been learned about the ζ Aurigae binaries from early photographic spectroscopy and single-cell photoelectric photometry. All the same, the introduction of CCD spectroscopy in the 1980s and the advent and subsequent burgeoning of space-based data, especially in the ultraviolet, suggest a need to update Wright's review with the new results from those advances, and "Giants of Eclipse" (which is in fact appropriately dedicated to K.O. Wright) will now serve as that new reference.

“Giants of Eclipse” builds on the results derived from classical visible-wavelength spectroscopy by engaging the benefits of high-signal-to-noise CCD observations and then weaves in the additional data that have accrued from space missions and from the developing technologies of interferometry and asteroseismology, while at the same time maintaining a focus on the complementarity of that research to other important areas of astrophysics. That dual role will ensure the value of the book as a source of astrophysical information for many years to come.

The seven chapters that comprise “Giants of Eclipse,” though written by a consortium of 12 experts, have been integrated almost seamlessly into a whole that offers enjoyable reading both for those with a general interest in astronomy and also for specialists, professionals, and students of eclipsing binaries, evolved cool stars, stellar atmospheres, and stellar evolution.

Villanova, USA Edward F. Guinan

Acknowledgements

To every book there is a unique set of complexities. The ones that beset us in the present instance derived from the complexity of the topic itself. Although the 1970 publication (in a refereed journal) that we planned to update had a single author (Dr. K. O. Wright), both the subject material and the available methods of attack had evolved and burgeoned sufficiently since then that we needed to call on many different sources of expertise—10, to be precise—plus 2 others whose contributions, while relatively short, were as profound in their own areas as the rest. It is to those 10 co-authors and contributors that we owe our most sincere gratitude, not only for their expert compositions but also for allowing us to demand—and have—their time and attention when it was convenient to us. Each leads a busy academic life, yet each proved capable of those extra achievements which (so the adage attests) busy people do best. To them we offer our thanks for fine science and thorough work, for prompt co-operation and rapid responses, for flexibility and good nature, and (mirabile dictu) for remaining our friends.

For their part, several of those authors have asked to include an acknowledgement of individual funding support, and we do so hereunder:

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Chapter 1
The ζ Aurigae Binaries

R. Elizabeth Griffin and Thomas B. Ake

Abstract This opening chapter provides a brief historical overview of the ζ Aur stars, with a focus on what K.O. Wright, his predecessors and colleagues at the Dominion Astrophysical Observatory, and his contemporaries further afield, achieved during the era of pre-electronic data. It places the topic within the framework of modern observing, data management and computing, outlines the principal features of the chromospheric-eclipse phenomena which single out the ζ Aur binaries for special study, and describes the considerable potential which this remarkable yet very select group of stars offers for increasing our understanding of stellar physics.

1.1 Introducing the ζ Aurigae Binaries

The Galaxy contains over 10^{10} stars, and quite a number of them have at some time, or will soon be, classified in some manner, and placed in the 'boxes' that are the tools of the scientific statistician. Many will exhibit normality (however we define that); at least as many more will exhibit deviations from that normality, and the statistics will reveal that certain of the trends which can then be discerned are astrophysically significant. Yet it took only one single star in that entire Galactic sample to demonstrate a quite unanticipated but very remarkable phenomenon—an atmospheric eclipse—which opened up a route to new science that had not previously even been imagined. It allowed us to observe directly a star's chromosphere—something that could only be done in the case of the Sun—and thereby to study those outermost regions where a star interacts with its own immediate environment, and into which it sheds material from its surface. The astrophysics which developed from that one star

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burgeoned into a substantial contributor to stellar physics; observers and modellers cornered international photometric and spectroscopic observing campaigns during the twentieth century, collectively requested major amounts of observing time on telescopes in space as well as on the ground, and still continue to wrest all possible information from both archived and new data. Studies of this star and a small handful of related objects also commandeered an AASTCS conference, *Giants of Eclipse*, held in July 2013 in Monterey, California. The star is ζ Aurigae.

1.2 History and Background

The history of this special field of astrophysics dates back nearly 90 years. The newly-completed 72-in. reflector at the Dominion Astrophysical Observatory (DAO) near Victoria, Canada, was being used to refine the radial-velocity (RV) orbits of stars recently flagged as binaries by the extensive Lick RV surveys. ζ Aur had already been classified as a 'composite-spectrum binary', a term coined before 1900 by the Henry Draper classification team at Harvard to describe a binary in which a cool giant star is paired with a much hotter and comparatively unevolved star. Although the giant is considerably more luminous that the dwarf, their flux distributions have quite different shapes, and in the blue and near-UV spectral region they are fairly comparable. The observed 'composite' spectrum results from the superposition of the spectra of the two components. One noticeable characteristic is that the plentiful, deep absorption features that are typical of the spectrum of a late-type giant appear substantially weaker than in a similar single star owing to the veiling effect of the flux from the hotter dwarf companion. In ζ Aur, whose hot component is a mid-B dwarf, that veiling is very pronounced in the photographic blue spectral region. When Harper noticed that in one of his spectra of ζ Aur taken at the DAO in 1924 the contribution from the hot component seemed to be *absent*, he surmised that it could be in eclipse (Harper 1924). The orbit then to hand was sufficiently accurate, and the duration of an eclipse sufficiently long, that the next event, as predicted by Bottlinger (1926), could not be missed, although only one eclipse in three was well enough placed for all-night observing. In early 1932 Guthnick showed Harper's surmise to be correct (Guthnick 1934).

But that wasn't all. Spectra obtained by Guthnick during ingress into the January 1932 eclipse, and by Beer during the 1934 September one (Beer 1934), revealed deep, narrow absorption features that waxed rapidly in intensity as ingress approached, and waned equally rapidly during egress. Most of those extra features corresponded to the familiar ground-state lines that are so prolific in a late-type spectrum, but included additional sharp cores in the Balmer lines (see Fig. 1.1). Furthermore, the shorter the wavelength, the longer totality appeared to last. These dramatic changes caught the attention of theoreticians, and in 1936 Menzel (Harvard) offered the explanation: although both stars were visible since the observed spectrum was still composite, the hot star was acting like a light-probe and shining through progressively thicker layers of the outer atmosphere of the K-type

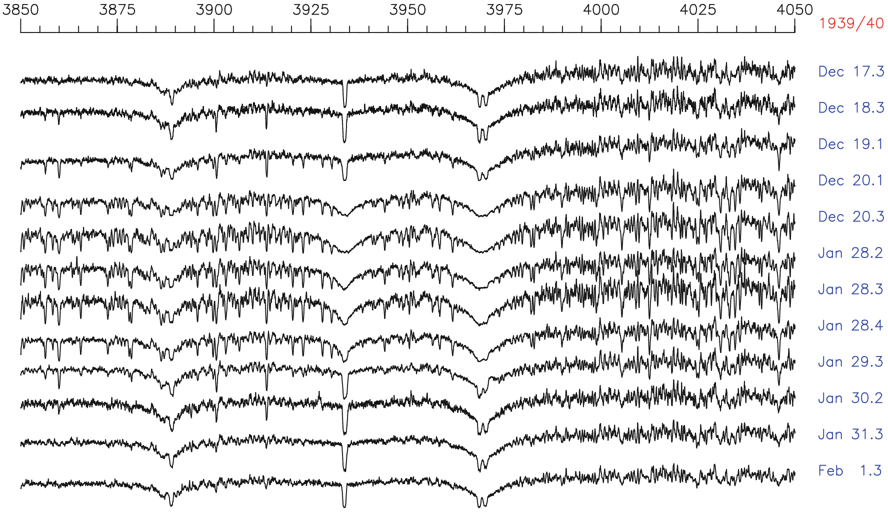

Fig. 1.1 The effects of chromospheric absorption observed during the eclipse of ζ Aur in 1939–1940. The original photographic spectra exposed at Mount Wilson were digitized at the DAO (see Appendix, Chapter 2, page 80). The spectra illustrated here are a representative selection of the full series. According to Kron (1940), first contact occurred on 1939 December 19 at 15:45 UT, with second contact ∼1.7 days later, on December 21 at 08:30; totality lasted for nearly 37 days, with mid-eclipse on 1940 January 8. Third contact took place about 0:00 on 1940 January 27, and fourth contact ∼1.7 days later

supergiant as it passed behind it towards first contact. In uncharacteristically graphic terms, Menzel likened the event to that of "a planet setting in a smoky atmosphere, disappearing before it reaches the horizon", its light as much extinguished as occulted (Menzel 1936). Figure 1.1 shows a sequence of spectra of ζ Aur observed near conjunction phases.

1.3 Chromospheric Eclipses

It was not difficult to explain Guthnick's observations *qualitatively*. As an eclipse approaches, the familiar composite spectrum, with its combination of broad early-type features mingled with numerous but weakened narrow lines from the cool primary, becomes complicated by the addition of a third spectrum, as the chromosphere selectively absorbs the hot star's radiation passing through it in the line of sight. Formed by pure absorption in a region of very low density, those chromospheric lines arise from atoms and ions in their lowest excitation states. They are typically very narrow and without wings, and the strongest ones can be almost black in the core as very little scattering takes place. As the light from the hot star traverses increasingly deep layers of the chromosphere, the narrow absorption lines strengthen noticeably until second contact, when the spectra of both the early-type star and the chromosphere vanish and only that of the cool primary remains. The reverse then happens from third contact onwards. A time-series of spectra like the one reproduced in Fig. 1.1 samples the column density of the chromosphere at different distances from the primary's limb, thereby providing unique information for modelling the density and temperature gradients in the neighbourhood of the secondary's projected trajectory—though constructing those models accurately can be an exacting challenge.

Calcium is one of the most abundant photospheric metals, and is readily observed in the blue or near-UV spectral region through its strong resonance lines of Ca II at λ 3968 and 3933 Å (Fraunhofer's *H* and *K* lines). The low temperature and rarefied conditions of a stellar chromosphere favour absorption from ground-state or low-excitation levels of once-ionized species, so the *H* and *K* features become very pronounced during a chromospheric (*a.k.a. atmospheric*) eclipse and effectively represent the chromosphere throughout much of its discernible extent. Other features, such as the four strong neutral iron lines between λ 3920 and 3930 Å, also show chromospheric absorption, but are only strong enough to be detected in the lowest, most dense, layers where the chromosphere merges with the 'upper photosphere'. In Fig. 1.1 the secondary star was partially eclipsed on December 20 and January 28—as verified by Kron's (1940) photometry—so the line of sight to it only sampled the lowest, most dense, chromospheric layers. The Ca II lines were so strong at those phases that they had by then developed pronounced damping wings.

The series illustrated in Fig. 1.1 was derived from one of several comparable sets of ζ Aur spectra recorded at Mount Wilson, mostly during the winter eclipses. A number of similar sets was obtained at the DAO (though poor observing conditions often interfered at that season), and also at several other observatories across the world. In the early years of ζ Aur research, monitoring the chromosphere was usually restricted to partial-eclipse phases and to the nights of deepest chromospheric absorption close to first and fourth contacts, when chromospheric lines are very plentiful. All the same, as Fig. 1.1 shows, the chromosphere of ζ Aur could still be detected at both the start and the finish of that series of observations. In fact, the giant's outer chromosphere extends to distances that are substantially greater than the radius of its photosphere, and can be detected spectroscopically for several weeks both before and after total eclipse. Faraggiana (1965) reported that, according to spectra of the 1963–1964 eclipse taken at Merate Observatory, the chromospheric *K* line first appeared about 38 days before first contact and vanished about 24 days after fourth contact.

1.4 The Field Widens

In 1950 two more systems, 31 Cyg (McLaughlin 1950b) and 32 Cyg (McLaughlin 1950a), were added to the collection of eclipsing composite-spectrum binaries, now collectively known as 'ζ Aurigae systems'. Though broadly similar to ζ Aur in nature, 31 Cyg and 32 Cyg present different characteristics of mass ratio, flux ratio and spectral types, as well as orbital period and inclination. The intensities and small-scale complexities of their chromospheric absorption lines also exhibited behaviour that was more capricious than in ζ Aur itself.

Well before 1950, the 'ζ Aur effect' had also been recognized by Gaposchkin (1937) in the M supergiant plus B dwarf which comprise the long-period binary VV Cep. The flux from the M star overwhelms that from the B star in the optical region, so the system is best studied in the UV. However, the changes which spectra of VV Cep manifest are greatly complicated by variable emission within the system, believed to arise mainly through the transfer of mass from the supergiant onto its companion, and by circumbinary and interstellar features, all of which are enhanced at UV wavelengths. The challenges and problems presented by VV Cep are sufficiently idiosyncratic that in this book they have been given a separate discussion (Chap. 3, page 85).

In 1978 *IUE* opened up spectroscopy at space-UV wavelengths, and the binary 22 Vul became the next new addition to the ζ Aur class when Parsons and Ake (1983) recognized not only the composite nature of its spectrum but also that it underwent an eclipse (Parsons and Ake 1984)—though only for about 8 days, unlike VV Cep in which an eclipse lasts for about a year and a half. As with VV Cep, the dominance of the flux from the supergiant primary (in this case of mid-G type) throughout the optical region explained why it had not been detected earlier from the ground.

The discovery of a total eclipse in HR 6902 in 1986 (Griffin 1988) was followed by the discovery of a partial one in HR 2554 (Ake and Parsons 1987). Suspected eclipses in the G8 III+A4 V binary τ Per, also confirmed as partial by *IUE* observations (Ake et al. 1986), were studied both spectroscopically and photometrically during its 1989 conjunction (Griffin et al. 1992). Recognition in 1990 that the relatively short-period composite-spectrum binary HD 223971 (G7 III+A2 V; $P = 50.1$ days) is an eclipsing system (Griffin et al. 1991) was itself eclipsed by the somewhat surprising discovery very shortly afterwards that γ Per (G7 III+A2 IV), a bright system ($V = 2.9$ mag.) with a period of 14.6 years, undergoes total eclipses that can easily be detected visually and last for more than a week (Griffin 1991b). These subsequent additions to the ζ Aur class contain G-type primaries of somewhat lower luminosity, and therefore of smaller physical size, than in the first five systems to be discovered, thus extending the scope of the information that can be extracted from a chromospheric eclipse but bringing new challenges in extracting it.

Along the way, one system was 'lost' from the class. δ Sge (M2 IIab + B9.5 V) had been reported by Hynek (1942) as exhibiting sharp, variable Ca II K-line cores suggestive of at least an atmospheric eclipse, and the system was forthwith dubbed a member, or probable member, of the class. Because the orbital period is 10 years it took time to re-observe it astutely with the right equipment before enough evidence was to hand to demonstrate that in fact its orbital inclination was a mere 35° or so rather than near the 90° which eclipses require (Griffin 1991a). The observed changes in the K-line core, which have since been examined at high dispersion, appear to be phase-related combinations of broad but weak absorption intrinsic to the late-B star, narrow interstellar absorption, and variable emission. Unlike the early-B star in VV Cep (described in Chap. 3), the B-type component in δ Sge is not energetic enough to produce its own emission spectrum—its photospheric spectrum is fully present and visible—so the emission is likely to be associated with the M-type primary. That emission may cause the photometric variability that has been widely reported (e.g., Demircan et al. 1990), and may be associated with low-amplitude periodicities in the radial-velocity residuals that have also been detected (Walker et al. 1995).

The positive identifications bring to 10 the number of known ζ Aur binaries. As a sample it is not large, and since no two cases are very similar there is little meaning in defining a norm. Some of the fundamental characteristics and descriptors of the systems have been assembled in Table 1.1. The values listed there are not new determinations, nor necessarily consensus ones, but have either been taken from various papers or have been recalculated and not yet published. The purpose of the Table is to show that the stars in question are all bright objects (all but one are visible to the unaided eye), that their periods range over two orders of magnitude, and that the eclipses which they exhibit are, except for the last two, rather difficult to discern by eye, though all except that of HR 2554 are more pronounced at shorter wavelengths. The range and types of chromospheric-eclipse phenomena which they encompass extend from the very dramatic to an apparent absence of visible information, though a null result is not without scientific significance. In fact the very diversity which they collectively exhibit speaks to the diversity of all cool-giant stars—their structure, evolutionary states, mass losses, and the extent to which small differences in the temperature or pressure gradient of the outer atmosphere can affect, or can be affected by, those parameters.

Yet while that diversity checks our ability to model *the* archetypal stellar chromosphere since in practice there seems to be no such entity, it demonstrates vividly the wide range of physical laws in play and brings home how wrong our *photospheric* models and assumed mass-loss mechanisms would be without that extra insight which the phenomena of atmospheric eclipses alone can provide. The reviews in the following chapters illustrate and discuss that richness and potential, and focus on observations made both from the ground and from space. When we reflect that it is only in the case of the Sun that a star's chromosphere can be observed directly, the true worth and exciting potential of these atmospheric eclipses begins to be appreciated. Finding ways to realize that potential is what this book is about.

1.5 Other Advantages Offered by the ζ Aur Stars

The ζ Aur systems not only provide unique information about stellar chromospheres, but they also occupy a special position within the wider context of stellar research. The mass of a star is generally considered to be its most fundamental parameter. The amount of mass in a star governs the rate at which it evolves, but