Combination variables: Insights on atomic spectra

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Double stars give us not only insight into stellar masses, dimensions, and luminosities (as has been appreciated for many years), but also clues as to the late stages of evolution, as in novae and combination variables, where late type giant or supergiant stars are paired with small, hot companions. Some even provide information on atomic spectra, notably iron, whose emission lines are displayed so prominently in objects such as XX Oph and RR Tel.

1 Introduction

Stellar astronomy of the nineteenth century was largely that of double stars observed visually. Only later were spectroscopic measurements and photometry applied to extend the scope of investigations to spectroscopic binaries and eclipsing systems. Under favorable conditions, from the latter data we obtained stellar masses and dimensions, but more was still coming. Stellar evolution studies broadened the picture still further. Consider the class of close binaries, whose two components were closely similar in mass and spatially not far separated. As they evolved, the very tiny mass difference begins to produce a profound effect. The more massive star, A, would swell up first and start to lose mass at an ever increasing rate. Much of this material may simply escape in space, but some might be captured by the companion which as it evolves begins to bloat up like its originally more massive companion star A. As star A further evolves, it loses its outer envelope entirely and shrinks into a hot, relatively small, compact object. Meanwhile the component B begins to expand as did A previously, with one important difference. Whereas ejecta from A fell usually quietly on B, that from B now fall often through a potential gradient to A's hot surface. This dumping phase can produce sometimes a nova-like outburst, which can occasionally rise to the full glory of a nova-outburst. After that there may follow a period of quiescence for awhile until more material falls from the companion which may resemble a normal K giant star.

Thus, a frequently observed situation is one in which the more highly evolved star has been stripped of its outer layers and the hot core is exposed. Occasional nova-like outbursts are observed. The star is unstable and variable. Sometimes the cool component is brighter, sometimes the hot star dominates, and in some systems the two components are about equal. In RR Telescopii the radiation from the hot component so dominates the brightness that the molecular contribution from fainter, cooler component scarcely can be detected (Thackeray 1977). Such an object is favorable for studying the rich atomic emission spectrum of the hot component and its hot, expanding envelope.

The typical situation is depicted schematically in Fig. 1. There is a compact hot star which excites a portion of the extended atmosphere of its cool, M-type companion. If the latter is sufficiently attenuated, it may emit characteristic lines of gaseous nebulae, e.g., the λ5007 line of [O III]. The bulk of the bright-line spectrum may come from excited gases of the M star envelope and much material which has escaped to form a small nebula around the star. The blue continuum comes from the hot component, while the absorption TiO bands originate in the envelope of the M-type star. The components may sometimes have comparable brightness throughout the visual region, but often the red component dominates save during the outburst.

2 Thoughts on the bright line spectrum of RR Telescopii

In certain favorable combination variables, such as RR Tel, both the line and continuum spectrum are dominated by the hot component. In this object we are favored by small internal motions which enable us to attain high spectral resolution and good identifications (Crawford et al. 1999). Over the years, extensive work has bee done by Thackeray (1950, 1952, 1953, 1955, 1977), McKellar et al. (1959), McKenna et al. (1997), to mention a few. The spectrum appears to be slowly (but not uniformly) rising in excitation.

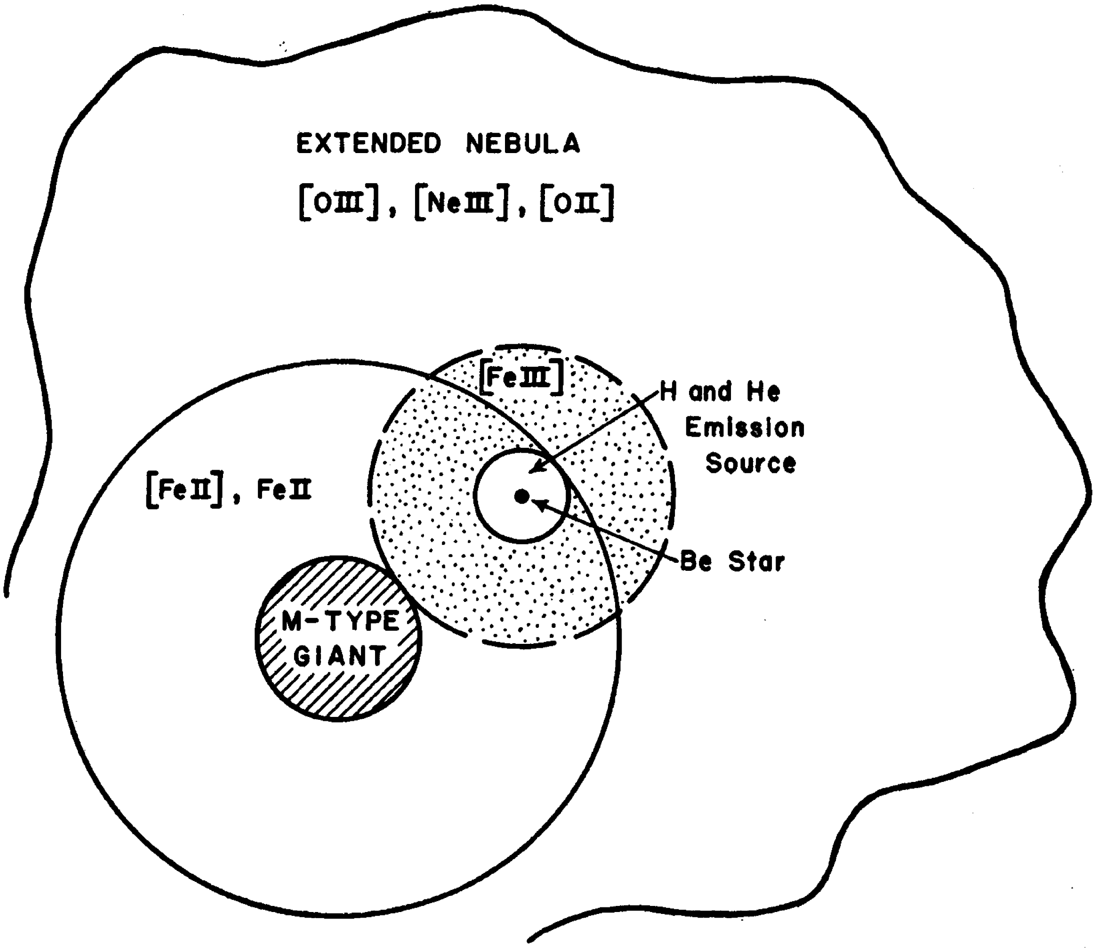

Fig. 1: The sketch model of BF Cygni adopted from Aller (1953)

Crawford et al. measured 811 lines from 3180 to 9455 Å, with a resolution of 50,000 – approximately twice as good as anything obtained heretofore. The excitation ranges from N I to Ni VIII, but most of the emission lines seem to be those of iron ions, from Fe II to Fe VII. The coronal iron lines are not seen on RR Tel, although they are seen in some recurrent novae, such as T CrB.

The sharp numerous lines offer splendid opportunities for unequivocal line identifications and ultimately line intensities. An early attempt to measure accurate line intensities was made by Faulkner and Aller at Mt. Stromlo in 1961 with a photoelectric scanner built by W. Liller at Michigan. Although the spectral resolution of 10 Å was woefully inadequate for most lines, some useful results seemed attainable. When we applied for more time we were not encouraged to come again to Stromlo. The next phase of the endeavor was carried out under congenial arrangements at Cerro Tololo, but we had to use a spectrograph with photographic plates. Thus we gained in spectral resolution but lost in accuracy. Aller et al. concluded that much of the emission came from strata at densities of the order of 10^6 - 10^7 atoms/cm^3, and electron temperatures $T_e \approx 20,000$ K. The abundances of Fe and Ni seemed comparable. Aller & Keyes (1974) compared photoelectric scanner observations obtained in 1961 by Faulkner and Aller with those found on 1972 from Cerro Tololo. The [Ne III] data seen to indicate a high $T_e \approx 18,000$ K. The picture is complicated by indications of vast density fluctuations within the shell and nebulous envelope of RR Tel. A most dramatic feature of the spectrum of RR Tel is the display of the spectrum of iron in its various ionization stages. From the work of Crawford et al. (1999) we may refer to their Fig. 1 which shows the spectrum of RR Tel between 4861 and 4949 Å.

There are three reasons why ubiquitous iron should be so important: (*a*) its cosmic abundance; (*b*) richness of its spectrum; particularly in low ionization stages, and (*c*) several ionization stages are frequently prominent simultaneously. Let us define the "abundance" A as $\log N(\text{element})/N(H) + 12$. On this scale, $A = 7.50$ for Fe, and the A-values for Mg, S, and Si are comparable for the "standard solar system" material. Iron is much more abundant than neighboring elements such as Sc, Co, Mn, Ni, and Cu, a factor which together with its rich spectrum enables it to play such a dominant role.

A second point is the richness of the iron spectrum, particularly the low ionization stages, Fe I, Fe II, and Fe III. Elements of comparable abundance and excitation potential such as Mg and S have ground configurations of equivalent p electrons while Fe with its low-lying configuration of $3d$ and $4s$ electrons offer much more intricate possibilities. The $4s$ electron is more tightly bound than the $3d$ electron, but if iron is ionized, the shielding of the $3d$ electron is less effective and in doubly ionized atoms the $3d^6$ configuration supplies the ground level of Fe III and the first excited configuration $3d^5\,4s$ well separated. In the important ion Fe+, $3d^6\,4s$ is the ground configuration, but the $3d^7$ configuration lies only 0.2 eV above it. Therefore, the levels arising from the terms of the two configurations will overlap so the Fe II spectrum will be very complicated. We cannot make a Grotrian diagram for Fe II as we would construct one for a simple ion like Mg of Si. Instead we have to make special energy level diagrams, each illustrating the features we want to emphasize.

We can construct such a rough Grotrian diagram to illustrate some of the most important features of the Fe II spectrum (compare to Netzer 1988). The energy levels of main concern to us fall in four groups. The ground level is of even parity. Roughly 3 eV above lie several levels also of even parity. Then, at about 5 eV are levels of odd parity. High levels at about 8 eV are odd levels. Transitions between the $\approx$3 eV even parity levels and ground even parity levels give strong forbidden [Fe II] lines. Transitions between $\approx$ 5 eV odd parity levels and $\approx$ 3 eV even terms give rise to strong optical permitted lines. Transitions between $\approx$ 8 eV odd levels and $\approx$ 3 eV even levels give rise to permitted UV lines. The point is that the great number of excited Fe levels gives a wealth of lines. In discussing the spectra of various Fe ions we can construct separate Grotrian diagrams for each transition array.

Continuing with a discussion of the Fe II spectrum, note that the normal configuration is $3d^6(*L)nl$, where nl normally denotes $4s$, $4p$, $4d$, and $5s$. The terms have different parents; e.g., many important terms and levels are based on $3d^6\,{}^5Dl$. The strongest $4s-5p$ lines are centered on 2500 Å. The separations $4p-5s$ and $4p-4d$ are similar; the former transition array is centered on 2700, the latter on 2300 Å. In the solar spectrum, the 2000 - 3000 Å region is dominated by Fe II. The lines can be described by the LS coupling scheme even if we have to use intermediate coupling to compute level positions and line strengths. Transitions in the $4s-5p$ scheme between LS terms built on different parent terms extend the actual wavelength region to farther in the UV and redward. Important Fe II multiplets based on low ${}^4F\,{}^4D\,{}^4P$ occur (see Johansson 1988). There are also strong high-level ($\approx$ 10 eV) lines.

An entirely different term system occurs because of electrostatic interactions; these interactions occur between electrons in doubly excited systems, thus in $3d^5(*L)nln'l'$ because the coupling between the two outer electrons nl and $n'l'$ is stronger than between them and the d electrons when $n=n'=4$. What we do is add a two-electron LS coupling configuration, e.g. $4ss\,{}^1S, 4s4p\,{}^2P$ to the grandparent configuration $3d^5$ in Fe IV. One important point is that double excitation can produce serious complexities. See the discussion by Johansson (1988). An atom may be excited to a level a fraction of an eV above the ground level. A second electron may be excited in the system.

Thus because of the extreme complexity of the spectrum of Fe II it will largely dominate the spectrum of any source in which it prevails. If the lines are broadened, as often occurs in quasars and AGN's, the result is likely to be a bright virtual continuum. At higher temperatures Fe II is likely to be replaced by [Fe III], Fe IV, [Fe IV], [Fe V], [Fe VI], and [Fe VII]. Thee lines provide a wealth of information on N_e and T_e in the layers producing the emissions, a panorama of the nebulosity surrounding the combination variable. Thus they provide the tools for investigating the gaseous envelopes of evolving stars. At the higher temperatures some of the best known of these are [Fe V], [Fe VI], and [Fe VII].

Considering here only emission lines, note those of [Fe II] and [Fe III] as well as permitted lines of the same ions are largely excited by electron collisions with $T_e \approx 10,000$ K. Hence any adequate quantitative treatment of these lines requires accurate A-values and collisional strengths, truly a formidable constraint. Electron capture and cascade plays a role, though not as important as in typical gaseous nebulae. Other processes must be considered. One of the most important is fluorescence. Because of the richness of the Fe line spectrum there are many self-coincidences as well as coincidences with lines of other elements. Coincidences with Lyman α are of significant importance. Hence a theoretical prediction of the iron spectrum can become extremely difficult. Consider the problem of ionized plasma. The factors contributing to the observed intensity of a particular Fe line will include:

(a) atomic parameters relevant to the particular level, such as A-values, collision strengths, ionization and recombination coefficients for the level involved, and charge exchange coefficients.
(b) The diagnostics, N_e and T_e of the plasma, which determine collisional excitations and some radiative excitations, recombinations rates, and collisional ionization rates.
(c) The radiation field affects all atoms. Fluorescence and other deviations from a Planckian

distribution are particularly important.

Some years ago a frontal attack was started via the Iron Project, an international effort to determine the basic parameters for the sundry physical parameters for physical processes occurring in all ionized plasmas from stellar interiors to stellar atmospheres, to gaseous nebulae, to interstellar medium, thus covering a vast range of densities and temperatures, from Fe I to Fe XXV (whose lines are seen in solar flares). When these computations are completed we should have the wherewithal to deduce from the measured intensities of Fe ion lines in a radiating plasma all the relevant diagnostics.

When we measure the bright line spectrum of a symbiotic star in detail we hope to get some clues as to the relative importance of these parameters. Some years ago it was even hoped that in some of these symbiotic stars or combination variables such as XX Ophiuchi we might even be able to find relative A-values for certain lines. Now, with the recognition of the importance of fluorescence, for example, and other limitations we realize that opportunities are very restricted. Nevertheless, Johansson & Cowley (1984) were able to identify certain Fe II lines originating from levels of this ion. The lines appeared in a stellar source where the plasma is substantially hotter than in the laboratory plasma which served as an Fe II source.

It cannot be overemphasized that a given line in a symbiotic star may arise from emissions at very different T_e and N_e. This phenomenon is shown by the [O III] lines in RR Tel whose profiles show that they must originate at three regions moving with different velocities. The line width of 14 km s^{-1} for [Fe II], 45 km s^{-1} for [Fe V], and 65 km s^{-1} for [Fe VII] all indicate strata moving at different velocities as different positions in the shell.

Perhaps the most attractive idea is that the nebula observed in symbiotic system is actually the wind of the M giant excited by the radiation of the hot component. This idea (Nussbaumer & Schmutz 1983) has been developed quantitatively by Nussbaumer & Vogel (1987). The problem is an extremely difficult one. In some respects it resembles that of a slowly evolving planetary nebula. But the problem is more troublesome. Not only there is a problem of spatial resolution, far more critical than in planetary nebulae, but we have to contend with the fact that the time scales of important processes like recombination may be comparable with times of expansion.

An additional factor which cannot be overemphasized is the clumpiness of the ejected envelope. This phenomenon was shown dramatically in the eclipse of 31 Cygni (McKellar et al. 1959). In the 1951 eclipse a K supergiant star passed in front of its A-dwarf companion. The radiation from the small star acted as an analyzing beam passing through the supergiant atmosphere. Measurements of the Fe lines in particular show great variations indicative of a cloud of material of greatly fluctuating density and geometrical thickness.

Hence phenomena of combination variables are complex. At one time it seemed that conditions could be stable enough for empirical parameters could be derived, as much as empirical gf-values were found from the curve of growth in the solar spectrum. That hope was not even roughly realized. Good A-values and other atomic parameters will come from the Iron Project. The spectral data can then yield important information on the structure of, and significant physical processes occurring in, these strata. The symposium chaired by Viotti on Fe II in non-LTE (Viotti et al. 1988) is particularly valuable. We hope an update will come soon.

The future offers many opportunities. Combination variables are favored in closely similar pairs. Component A must not yet advance to an inert white dwarf stage before component B begins active expansion. Combination variables resemble novae, but the puzzle remains. What governs the time between outbursts? We suspect that in novae it is the order of million years, although in recurrent novae the interval is much shorter. Why do objects such as T CrB show coronal lines?

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