THE EFFECTS OF CHROMOSPHERIC RADIATION ON THE CIRCUMSTELLAR CHEMISTRY OF EVOLVED STARS

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ABSTRACT. The physical and chemical properties of the circumstellar envelopes of evolved stars are strongly affected by the interstellar radiation field. Other sources of UV radiation should be similarly effective, and some examples are nearby stars (including companions), chromospheres, and the central stars of planetary nebulae. We consider the particular case of Alpha Ori, which has a chromosphere and an extended CSE with a small dust to gas ratio. Its properties are dominated by the chromospheric and interstellar radiation fields. The most common species are neutral atoms and first ions, and the electron fraction is high throughout the entire CSE, i.e. at least 10^{-4}. The abundances of neutrals peak in the outer CSE close to where the chromospheric and interstellar radiation fields are equal. An important application is KI, whose density has been measured by scattering. The theory predicts that the slope of the KI density should change from about -1.5 to -3.5 in the outer envelope, the exact values being determined by the temperature distribution. The mass loss rate implied by the KI density is of the order of 4×10^{-6} $M_\odot$ yr^{-1}.

1. INTRODUCTION

Circumstellar envelopes (CSEs) play an important role in the chemical evolution of the interstellar medium (ISM). Most of the mass influx from stars passes through the envelopes of evolved stars before entering the ISM. Foremost among the chemical processes which occur in the cool, low speed winds of giant and supergiant stars is the formation of dust. Both the formation of dust and the generation of the winds are major unsolved problems in astrophysics.

Several years ago it was believed that no other chemical activity occurred in these winds, i.e. CS molecules were frozen-in close to the stellar surface or in the region of

M. S. Vardya and S. P. Tarafdar (eds.), Astrochemistry, 379–385.

dust formation. More recent considerations indicate that other processes are operative, as discussed in the reviews by Glassgold and Huggins (1985) and Omont (1985, 1987). Up to now, most emphasis has been placed on the effects of interstellar UV radiation which penetrates deep into the envelopes and ensures that the molecules are broken up before entering the ISM. More particularly, the IS radiation affects the spatial variation of the circumstellar molecules and of their photodestruction products. In C-rich CSEs, the most important photodestruction sequences involve the step by step breakdown of CO, C_2H_2, and HCN into radicals, ions, and atoms and produce a chemically active region in the middle of the CSE, typically at distances of 10^{16} cm to 10^{17} cm from the star.

In addition to producing abundance variations and chemical activity, UV radiation affects the ionization of CSEs. In this paper, I will first mention some astrophysical situations where radiation sources other than interstellar are important, and then discuss the role of chromospheric radiation on the well studied CSE around Alpha Ori.

2. TYPES OF RADIATION SOURCES

It is useful to group the astrophysically interesting sources into several classes:

A. Mean Interstellar Field

B. Nearby Sources
   1. early type or hot companion, e.g. Alpha Sco and R Aqr.
   2. single, dominant O,B star, e.g. NML Cyg
   3. cluster of stars

C. Internal Sources
   1. chromosphere, e.g. Alpha Ori
   2. planetary nebulae stars, e.g. NGC 7027, CRL 618
   3. shocks, e.g. in planetaries and Mira variables.

The effects of the mean interstellar radiation field have been studied in some detail, but early type companions and nearby O,B stars have been considered only from the point of view of the effect of the CSE on the morphology of the HII region. For example, Hjellming and Newell (1983) mapped the radio continuum emission around Alpha Sco, an M supergiant with an early B companion, and deduced a mass loss rate of 2×10^{-6} $M_{\odot}$ yr^{-1} by modeling the B star's HII region. They also detected an ionized wind similar to that observed for Alpha Ori (Newell and Hjellming 1983). Beacause the separation of the two stars is about 10^{16} cm, we do not expect to find many molecules in Alpha Sco. NML Cyg is an unusual evolved star

https://doi.org/10.1017/S0074180900154336 Published online by Cambridge University Press

with H_2O, OH, and SiO masers that is partially surrounded by an HII region. Morris and Jura (1983) identify the source of the ionization as the most luminous member of the nearby Cyg OB2 association, 2 kpc from the sun. By modeling the H II region, they find that the mass loss rate is of the order of 10^{-4} $M_{\odot}$ yr^{-1} and that the CSE remains neutral out to 10^{18} cm. This result is consistent with the existence of molecules such as OH and CO; thermal CO emission has been detected recently in NML Cyg by Zuckerman et al. (1985). Planetary nebulae offer some of the most interesting examples of internal sources of UV radiation, particularly in the context of evolution from the previous CSE stage, but little quantitative modeling of these situations has yet been been carried out.

In addition to stellar UV radiation, the CSE may be exposed to a localized or otherwise high level of X-rays or cosmic rays. The above classification could be used in these cases. The effects of the mean cosmic ray flux have been investigated recently for the case of C-rich CSEs (Glassgold, Lucas, and Omont 1985), but no detailed consideration has been given yet to nearby or internal sources.

3. IONIZATION SOURCES IN IRC +10216 AND ALPHA ORI

These two nearby (about 200 pc) objects are among the best observed CSEs and are therefore of great interest for theoretical models. Omont (1985, 1987) has reviewed the physical and chemical properties of C-rich CSEs, with emphasis on IRC +10216, and I will discuss Alpha Ori in the next section. Here I consider the evidence for ionization sources in these familiar objects.

Figure 1 shows far IR and radio continuum measurements for Alpha Ori. An extrapolation of the 16-39 micron data (Forrest et al. 1979) passes through the 400 micron point (Sopka et al. 1985), but the radio measurements deviate below 90 Ghz. The dashed line is the blackbody flux for a star of radius 0.02", temperature of 3800 K, and 200 pc distant. The excess radio emission is consistent with a partially ionized chromosphere with a peak ionization level of a few percent and temperature of about 8000 K. There is ample additional evidence for the existence of a chromosphere in Alpha Ori, such as self reversed optical absorption lines, characteristic UV emission lines, and extended images in H alpha recombination radiation.

A similar plot for IRC +10216 is shown in Figure 2. The solid line is a fit to the 25-1000 micron data (from Sopka et al. 1985). Its extrapolation passes through most of the radio observations. The exception is the 6 cm VLA result of Spergel et al. (1983), which is a 4 sigma measurement and not quite a definitive detection. It would be of considerable interest to have better S/N measurements at 6 cm (and other nearby wavelengths) to determine whether there is any excess radiation above that expected from the CS dust and the photosphere itself.

Unlike the case of Alpha Ori, the evidence for an internal ionization source in IRC +10216 is not strong. In this case the ionization of the outer CSE is dominated by cosmic rays and penetrating IS UV radiation. The run of ionization and the chemical effects of various ions have been calculated by Glassgold, Lucas, and Omont (1985).

4. MODEL IONIZATION STRUCTURE FOR ALPHA ORIONIS

Previous theoretical work addressed a variety of pheneomena relevant to this CSE (Weymann 1962, Bernat 1976, Jura and Morris 1981, and Clegg et al. 1983). We have been developing a comprehensive model for Alpha Ori, and our first results (Glassgold and Huggins 1985) focus on the ionization and closely related properties of the outer CSE (beyond the region of dust formation, or 10^{15} cm). Important diagnostic species are CO, in emission at 1.3 mm (Huggins 1985, and references therein) and absorption in the IR (Bernat et al. 1979), and KI, observed by scattering of the resonance radiation at 7700 A (Honeycutt et al. 1980 and Mauron et al. 1984). The weak CO emission is confined to a region less than 30", but the KI can be detected out to at least 60". Recent abundance measurements by Lambert et al. (1984) show that C and O are only moderately reduced relative to the sun, so only a small fraction of the carbon in the CSE is in the form of CO. Similarly, the weak IR emission (c.f. Figure 1) implies that the dust to gas ratio is reduced by at least 10 relative to the ISM and other CSEs. Thus a reasonable first step to understanding the physical properties of this CSE is to ignore the chemical activity associated with the formation of dust and molecules.

A major theme of our analysis of the Alpha Ori CSE is the competition between the IS and chromospheric UV radiation fields. Figure 3 shows the latter, as deduced from satellite observations. The dashed line is an extrapolation into the range from from 1200 to 912 A, where there are no measurements at present. Photo rates calculated with this flux vary as $G'(R/r)^2$, where $R = 7.5 \times 10^{13}$ cm is the stellar radius (assuming a distance of 200 pc), and G' is typically a million times larger than the corresponding IS rate. Thus chromospheric radiation dominates for $r < 10^{16}$ cm, and IS radiation for $r > 10^{17}$ cm. For mass loss rates less than 10^{-5}

$M_\odot\ yr^{-1}$, H^+ recombines in the inner envelope, and the chromospheric and IS radiation fields maintain the heavy ions with IP < 13.6 eV fully ionized. Thus the electron fraction is equal to the total abundance of all such ions, i.e. $4x10^{-4}$.

The KI measurements provide an interesting application of the theory. The results are illustrated in Figure 4 for our "standard" model, which uses the abundances of Lambert et al. 1984, a mass loss rate of $4x10^{-6}\ M_\odot\ yr^{-1}$, and the temperature distribution 1800 K $(10^{15}$ cm/r)). The theory predicts that the slope of the KI density should change from about -1.5 to -3.5 in the outer envelope. The measurements have been fit by power laws with slopes -1.65±0.02 (Honeycutt et al. 1980) and 2.5±0.8 (Mauron et al. 1984); these slopes agree within the errors. The theory can be brought into close agreement with the absolute density of either experiment by simply changing the mass loss rate by a factor of two.

5. CONCLUSION

The above discussion of the Alpha Ori CSE (based on the work of Glassgold and Huggins, 1985) relates the atomic abundances to the chromospheric and interstellar radiation fields, and to the temperature distribution. It is likely that the molecular abundances and the amount of dust are also affected by these same quantities. Future extensions of the theory will include detailed considerations on the thermal and molecular proerties of the envelope.

In a more general context, Alpha Ori is an example of an M supergiant whose CSE has only modest amounts of dust and molecules. In certain cases like Alpha Sco, an early type companion may be responsible for this type of situation. Several authors have noted that dust emission is anti-correlated with the strength of the chromosphere (Jennings and Dyck 1972, Hagen, Stencel, and Dickinson 1983, and Jura (1985). Using the results of Hagen et al., M giants and supergiants can be classified into 3 groups according to the strengths of the chromospheric self-reversed K lines and the 10 micron dust emission, i.e. i) no 10 micron emission, ii) no self reversed K feature, and iii) both present. The last, intermediate class, represents 25% of the sample, and includes Alpha Ori. It would be of interest to have more detailed measurements of the dust and neutral atomic and molecular constituents of these intermediate CSEs as a guide to understanding the observed anti-correlation between dust and chromospheric activity.

This research has been partially supported by NASA grant NAG-630.

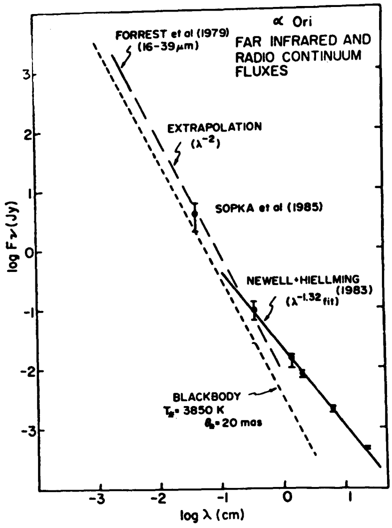

Fig. 1: Far infrared and radio observations of Alpha Ori.

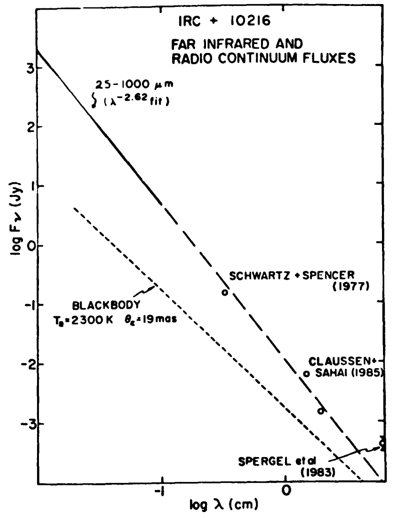

Fig. 2: Far infrared and radio observations of IRC +10216.

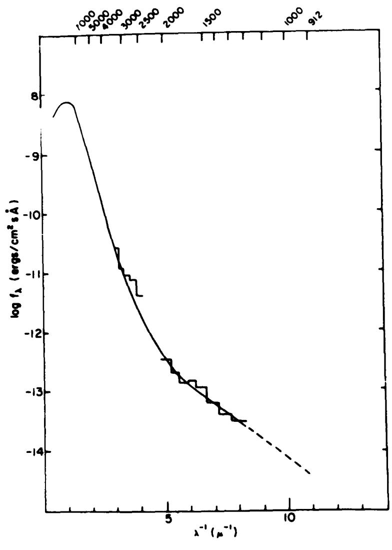

Fig. 3: Measured UV flux from Alpha Ori.

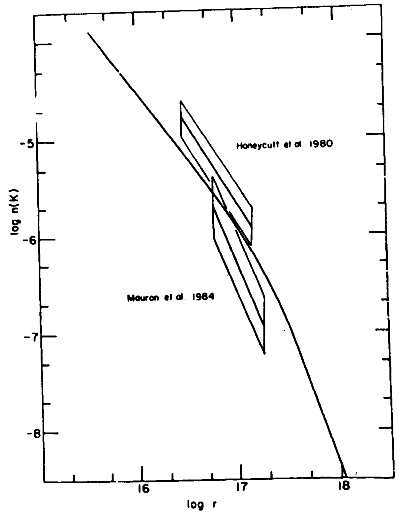

Fig. 4: KI density. The solid curve is the theoretical model of Glassgold and Huggins (1985), and the boxes are the observations of Honeycutt et al. (1980) and Mauron et al. (1984).

https://doi.org/10.1017/S0074180900154336 Published online by Cambridge University Press

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