RADIATIVE ACCELERATION AND ULTRAVIOLET RESONANCE LINE PROFILES IN OB SUPERGIANTS

J. B. HUTCHINGS

Dominion Astrophysical Observatory, Victoria, B.C., Canada

1. The Observations

The rocket spectra taken by Morton *et al.* (1967) were used as a basis for the investigation. These are in the far ultraviolet region of the Orion supergiants δ, ε, ζ Orionis. Because of the similarity in spectral type and luminosity of these stars and the great strength of the shifted resonance lines it was possible to derive a mean P Cygni profile (standard error 5% of the continuum) representing a typical single ultraviolet resonance line for a star of spectral type $\sim$B0, $M_v \sim -6.2$. This is the 'observed' mean profile in Figures 2 and 3.

2. Line Profile Calculations

Profiles were calculated for models of extended envelopes similar to those derived for the very high luminosity stars with higher mass loss (Hutchings, 1968). Only Doppler-broadened radiative and scattering interactions are included, and the integration is performed out to several radii from the stellar surface. An accelerating velocity field is necessary to produce the extreme P Cygni profiles observed and the line shape is dominated by the form of the velocity field and the dependence of the resonance line ion density on height above the star. Proceeding empirically it became evident that the density-height relationship differed considerably from that expected from LTE considerations, and an optimum profile fit was obtained with the velocity field (1) and the shell density relation shown in Figure 1. It is seen that the resonance line ion population (primarily Si IV and C IV) increases outwards for a considerable distance from the stellar surface. The profile calculated is still not a good fit to the observations, but is improved greatly by the addition of a 'zero height line profile' at the base of the envelope, which accounts for the absorption line formed by the low-lying higher density layers of the atmosphere. This zero height profile was taken from calculations found in the literature. The initial and improved calculated profiles are compared with the observed in Figure 2.

3. Radiative Acceleration

Using the velocity field derived we may calculate the number of radiative excitations undergone by a typical resonance line ion at different heights as it passes out through the extended envelope, taking into account radiation dilution and the absorption line strength between the ion and the surface. From the limb darkening and the solid angle subtended by the photosphere at different heights, the net absorption of outward

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momentum by the resonance line ions can be derived. The ratio of momentum absorbed to acceleration produced is seen to increase and level off in the outermost layers of the envelope. Assuming that the acceleration is produced by the radiation in this way, it is possible to calculate the rate of collisional de-excitation of the reso-

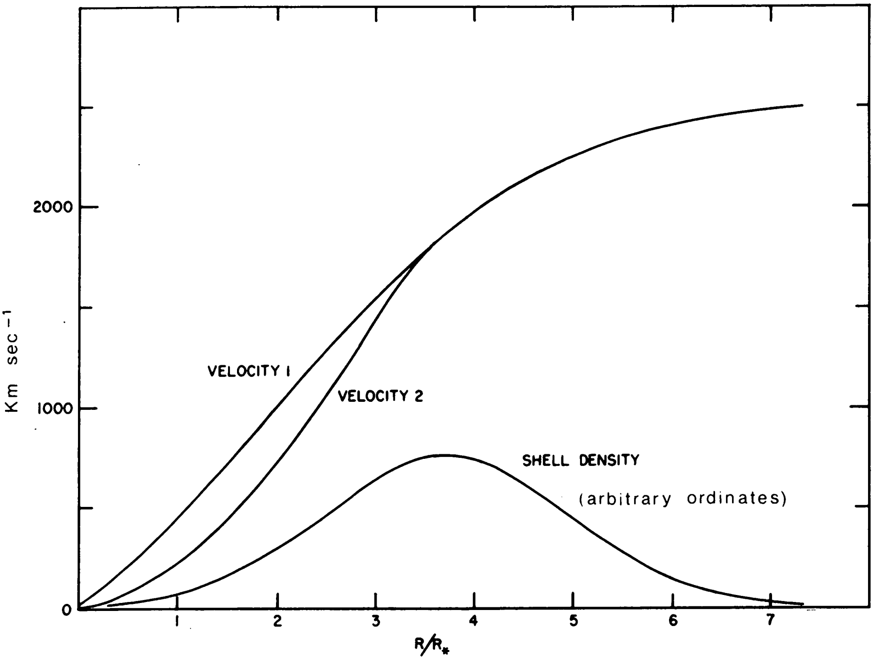

Fig. 1. Velocity and resonance line ion density as a function of height. Velocity in km sec^{-1}; density in arbitrary units proportional to number of ions in a shell of constant thickness.

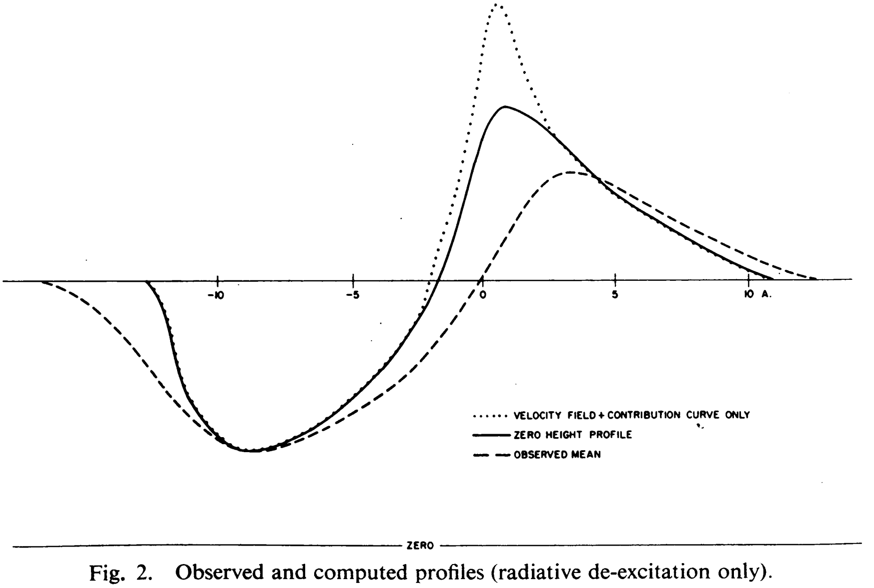

Fig. 2. Observed and computed profiles (radiative de-excitation only).

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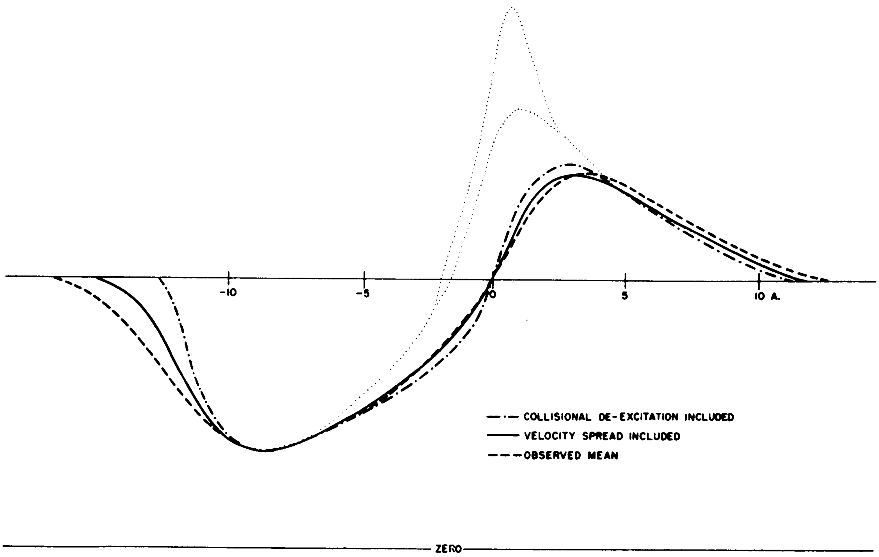

Fig. 3. Observed and computed profiles taking into account collisions.

nance line ions as a function of height, and hence to derive the density of the total atmospheric mass as a function of height. From this the acceleration of the entire atmosphere by transfer of momentum from the radiation, via the resonance line ions, to the atmosphere as a whole, is calculated. The mean total density out to some 4 stellar radii is high enough that the whole mass must have the same velocity, so that the entire calculation described in this section has to be iterated until the resonance line ion and total velocity fields are the same out to this height. This results in the velocity field (2) in Figure 1, a mean total density similar to that derived for the high mass-loss stars, and an atmospheric structure whose mass-loss rate is the same at all heights.

A check on the self-consistency of the entire argument is obtained by calculating the resonance line profile with the new velocity field, and including the derived rate of collisional de-excitation. This is shown in Figure 3, and it is evident that a very satisfactory fit is achieved. It is therefore proposed that the atmospheric structure derived is a valid crude representation of the envelopes of the stars observed.

4. Mass Loss

At present it is not possible to fix a zero point to the density of the expanding atmosphere, from the resonance line calculations. However, high-quality ground-based observations are available of the Hα line in these stars and this line shows a weak P Cygni profile in the mean (it is variable) with a velocity displacement of some −150 km/sec. Previous calculations of Hα profiles (Hutchings, 1968) have indicated the density and radiation dilution at which this line starts to show emission, and fixing these figures to the derived velocity field provides a crude mass-loss rate of some 10^{-6} $M_\odot$/year. This figure is in agreement with that derived by Morton *et al.*, and is consistent with the higher values derived for the higher luminosity OB stars studied. It is therefore suggested once again that radiation pressure is responsible for the mass loss from massive early-type stars.

(A full account of this work will be published in *Monthly Notices Roy. Astron. Soc.* in due course.)

References

Hutchings, J. B.: 1968, *Monthly Notices Roy. Astron. Soc.* **141**, 219 and 329.
Morton, D. C., Jenkins, E. B., and Bohlin, R. C.: 1967, *Astrophys. J.* **154**, 661.

Discussion

Solomon: In any mass loss by radiative acceleration, the maximum rate of mass loss is determined by the maximum momentum available in the radiation which is doing the acceleration. In the case of resonance line radiation this is the momentum in a line-width when the flow is at the sonic point. For O and B supergiants this amounts to about 2×10^{-8} $M_\odot$yr^{-1}. Therefore the rates quoted by Hutchings of 10^{-6} $M_\odot$ yr^{-1} violate the conservation of momentum.

The models you presented have been fitted with Hα observations to determine absolute values of the density at a particular velocity which then gives the mass loss rate. However, if instead of Hα, the density is determined by some other ion such as N v (that is, the electron density is fixed by the recombination rate necessary to give the observed N v) then the mass loss rate will be much less than 10^{-9} $M_\odot$ yr^{-1}. This makes it impossible to determine the mass loss rate in this manner since a large discrepancy of a factor of 10^3 is present in trying to reconcile two observed lines.

Hutchings: The observational results presented at this meeting have shown that there is not only one line which causes the atmospheric acceleration. In the case of the Orion supergiants there are six well established shifted lines and to judge on the results of Smith, who has found oxygen and sulphur lines as well, the assumption made in my paper of 10 lines seems a reasonable one. I am not clear how wide a linewidth is in Solomon's terminology but should point out that these lines have absorption widths of some 10 Å. Solomon's figure of 2×10^{-8} $M_\odot$ yr^{-1} should then be increased at least to 2×10^{-7} for the Orion stars, and in the case of more luminous stars or stars with P Cygni characteristics throughout the spectrum, to 10^{-5} or higher. While the zero point of my mass-loss figures leaves something to be desired I do not think they violate the conservation of momentum as suggested.

The fact that the mass loss rate is so much lower as calculated from the high-energy ion recombination rates serves to emphasize two points. Firstly that non-LTE equilibria apply in these extended envelopes, as is obvious from the ionisation-height relations, and secondly that most of the momentum is transferred from the high energy ions to the remainder of the atmosphere by collisional interactions.

Underhill: In the case of Wolf-Rayet stars a wide range of excitation is often seen among the emission lines and it is suspected that this is due to collisional excitation from high-energy particles emitted from the photosphere. Might not such a process be important in the stars you are discussing?

Hutchings: In the Orion supergiants the density of the outer envelope is low and collisional excitation is probably unimportant. It may be far more important in stars with greater mass loss such as the Of and W-R stars. As far as the relative population of high-energy ions is concerned there is no satisfactory theoretical approach at present. We must therefore simply accept that the populations of several high-energy ions reaches a peak in the outer layers (2–5 R_*), presumably, primarily by radiative processes.

Deutsch: If matter flows up through the base of the atmosphere, it will transport momentum which is additional to your radiation limit of L/c^2.

Hutchings: At present the sole mechanism of acceleration considered is momentum transfer from the resonance lines. The L/c^2 limit applies to each line which contributes to this process, so that we may increase the limit by the number of lines. In the extreme case of P Cygni there may be an acceleration mechanism action through some hundreds of spectral lines.