IUE and La Silla Observations of Mass Loss in the Magellanic Clouds

F. Macchetto, ESA, ESTEC, Noordwijk

Introduction

The phenomenon of mass-loss in hot stars has been known for a good many years. The strong stellar winds which are the manifestation of this phenomenon are observed as broad emission lines in the spectra of hot stars. In a number of cases the emission is red-shifted from the laboratory wavelength and a blue shifted absorption component appears; this is the so-called "P-Cygni" line profile as it was first seen in the spectrum of the star P Cygni.

Although the mass-loss phenomenon was first discovered and studied from the ground, it was not until the advent of rockets and satellites, which allowed observations to be made in the ultraviolet, that its extent and importance were fully realized. The reason for this is easily understood if one remembers that most of the resonance lines of neutral and ionized ions of the most abundant elements such as H, He, C, N, O, Si, S, Fe and Mg all fall in the ultraviolet region of the spectrum. And it is precisely these lines that are the most sensitive indicators of the occurrence of mass-loss.

The first extensive sample of hot stars showing mass-loss was obtained with the Copernicus satellite. These observations were however limited to the brightest and therefore nearest stars. The launch of IUE in January 1978 has allowed these studies to be greatly extended. It has been possible, for example, to survey at high spectral resolution (~ 0.1 Å) a complete sample of galactic stars and to establish that significant mass-loss occurs only in those stars brighter than $M_{BOL} \simeq$ 5 or 6 (Lamers, de Jager, Macchetto, in press). Furthermore, the high efficiency of IUE in its low-resolution mode (~ 6 Å resolution) makes it possible to observe stars of magnitudes between 11 and 13 in reasonably short times. This magnitude interval is just what is required to study the early-type stars in the two nearest galaxies to our own, namely the Large and Small Magellanic Clouds.

With this possibility in mind, P. Benvenuti, S. D'Odorico, C. Chiosi and myself submitted a proposal to study such stars with IUE and at the same time submitted a proposal to carry out photometric and spectroscopic measurements of the same objects with the ESO telescopes. Needless to say both proposals were accepted (or I would not be writing this article today!)

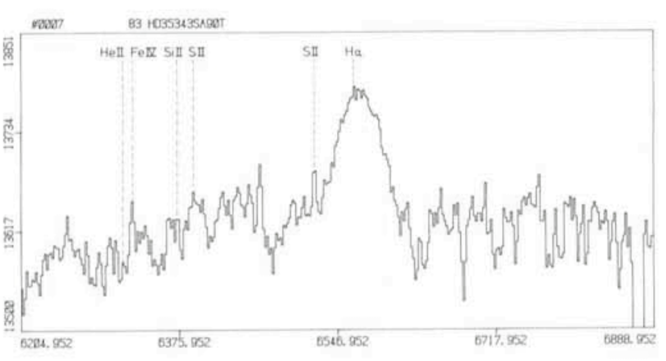

Fig. 1: *Red spectrum of the Bep star HD 35343 (SK 94) in the Large Magellanic Cloud. The most prominent emission line in this spectrum is Hα. The half-width at zero intensity of this line, measured towards the red wing, is 45 Å, corresponding to an expansion velocity of 2,057 km s^{-1}. (ESO 1.52 m telescope and Boller & Chivens spectrograph).*

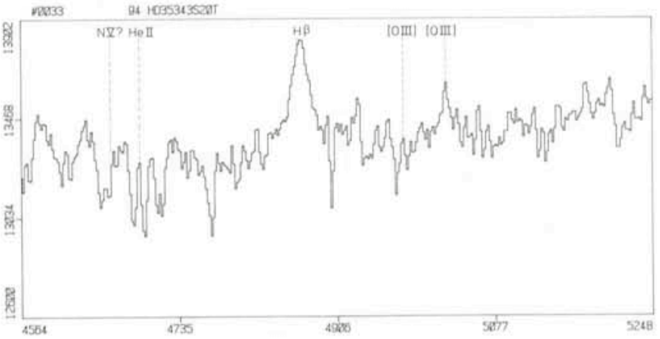

Fig. 2: *This spectrum of HD 35343 shows [O III] λλ4958, 5007 and He II λ4686 in emission, in addition to the strong and broad Hβ line (ESO 1.52 m telescope and Boller & Chivens spectrograph).*

Why do we want to study the mass-loss process occurring in stars of another galaxy? The reason is that we still do not understand how the mass-loss process works in detail. We know, or believe we know, fairly well what happens once the mass is ejected from the star and accelerated outwards. But we have little knowledge of why the mass-loss occurs, of what it is that pushes the matter out at velocities higher than the local sound speed or of what mechanism is responsible for accelerating the matter to the large terminal velocities (up to ~ 5,000 km/sec) observed in these stars.

We must therefore look for clues to solve those problems. One of the clues is the chemical composition. From theoretical models we expect the mass-loss to be dependent on the detailed chemical composition of the star. This is where the Magellanic Clouds can provide a unique test-bed. We know that the chemical composition of the Magellanic Cloud stars differs from that of stars in our own galaxy. We therefore expect to see direct evidence of this in the mass-loss characteristics of the hot stars in the Clouds. Of course by carrying out this study we will also extend our knowledge to the interplay of the different parameters such as temperature, luminosity, gravity, etc. that affect the mass-loss process.

Finally the effects that the mass-loss has on the evolution of hot stars can be studied, these observations serving as a test of the theoretical evolutionary models that exist.

The Observations

The strategy of observations was first to obtain U, B, V and Hβ photometric data, which in many cases were either poor or simply not available, then to carry out spectroscopy in the visible and a few months later to repeat and extend the spectroscopy in the visible and obtain simultaneous IUE observations in the ultraviolet. One reason for this was that observations separated by an interval of a few months would allow us to establish whether there was any spectroscopic variability. An additional consideration was that in the available IUE time we could not observe all the stars in our list and therefore a selection based on the visible data had to be made.

Photometric observations of 22 stars in the LMC and 7 in the SMC were carried out with the ESO 50 cm photometric telescope on La Silla, in September 1979. The diaphragm used was 15 arcsec in diameter. The U, B, V and Hβ photometric results are the average of three or four nights of observations. Night-to-night deviations were at most one or two tenths of a magnitude in V. The photometric standards used were taken from the E-region standards for U, B, V and for H_β from the photometric list of Crawford and Mander (1966, *Astron. J.* **71**, 114). Spectroscopic observations were carried out in September 1979 and January 1980 with the ESO 1.52 m telescope and the Boller & Chivens spectrograph. In September the dispersion used was 114 Å/mm. Recording was with a two-stage EMI intensifier tube and baked IIIa-J plates. In January the dispersion used was 60 Å/mm. Recording was with a three-stage EMI intensifier tube and baked IIIa-J plates.

Observations were carried out with IUE in January of those stars that had not already been studied by other investigators. These were obtained within hours of the ground-based observations from La Silla.

IUE observations of several other stars in our list had been made by other European and U.S. astronomers, and thanks to the IUE "six months" rule (i.e. the data become available to everyone six months after completion of the observation) we will soon be making use of it ourselves to enhance our statistical basis.

Some Early Results

We have not yet reached a point in our analysis where we can answer the many questions that arise, but we can give some general conclusions. (Preliminary results of this investigation have been published; F. Macchetto, P. Benvenuti, S. D'Odorico and N. Panagia, Proceedings of the Second European IUE Conference, Tübingen, 26-28 March 1980).

A significant fraction of the stars observed show mass-loss, as indicated for example by broad Hα emission or by P Cygni type profiles in the UV lines.

As an illustration of the results obtained, Figures 1, 2 and 3 show the spectrum of the star HD 35343 (SK 94). This star is classified as Bep in the Sanduleak catalogue and shows a large number of emission and absorption lines.

The most prominent emission lines in the visible are those of the Balmer series of Hydrogen of which Hα and Hβ are shown in Figures 1 and 2, respectively. The profiles of the lines appear to be asymmetric. It is not clear if this is due to the contamination by absorption lines of other atoms in the blue side of each of the lines or if these are real P Cygni-like profiles.

The half-width at zero intensity measured towards the red wing is 45 Å for Hα, corresponding to an expansion velocity for the wind of $V_{exp} \simeq 2{,}057$ km/s. The equivalent values for Hβ are 24 Å corresponding to 1,580 km/s and for Hγ the width is 12 Å corresponding to 830 km/s. Other emission lines in the visible are those of SII 6521 and 6386, SiII 6371 and 5915, FeIII 6323, HeII 6310 (weak) 4686 (strong) and 4200 (strong), [OIII] 5006 and 4958, SiIII 4532 and 4567 and SIII 4478.

In the ultraviolet region the following lines are found in emission: NII 1758 and 1748, HeII 1640, CIV 1550 and 1549, SiIV 1394 and 1403 and NV 1239 and 1243. The

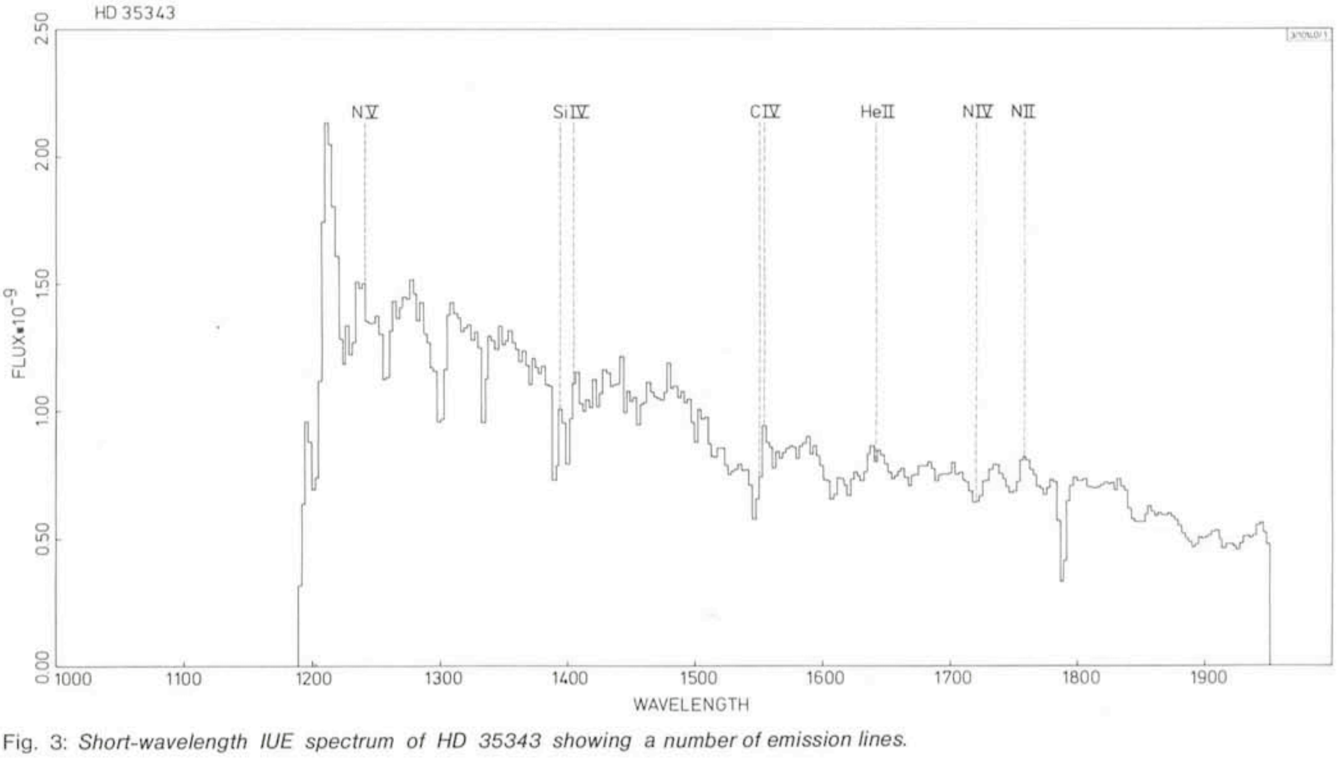

Fig. 3: *Short-wavelength IUE spectrum of HD 35343 showing a number of emission lines.*

wind velocity as measured from both the HeII and CIV profiles turns out to be 1,550 km/s which is significantly lower than that measured from Hα. This may be due to the depletion of hard ionizing photons which restrict the presence of CIV to regions closer to the star.

Discussion

It appears that in a broad sense the properties of the mass-loss process in the hot stars of the Magellanic Clouds and those of our own galaxy are very similar, although differences of detail, as already shown by Hutchins (*Ap.J.* April 1980, **237**, 285), can be seen and will be further investigated.

Of particular interest is the confirmation of a correlation found for galactic OB stars (Panagia and Macchetto, in preparation), between the terminal velocity and the effective temperature. A similar correlation between terminal velocity and excitation class has been found by Willis (Proceedings of the Second European IUE Conference), for WN stars. In both cases the higher the effective temperature the higher is the terminal velocity. In addition, for all high-temperature (or high-excitation) stars the momentum carried by the mass-loss ($\dot{M}V_\infty$) exceeds the momentum that the stellar radiation can release to the wind through *single* scatterings, by factors of between five and ten.

Clearly a more efficient mechanism for the wind acceleration is required. Such a mechanism has been proposed by Panagia and myself. It consists of the multiple scattering of hard ultraviolet photons in the approximate range 200 Å to 500 Å. In a qualitative way the mechanism can be described as follows. In the wavelength range 200 Å to 500 Å there are of the order of one hundred strong atomic and ionic lines. The average separation between lines is then of the order $c\,\Delta\lambda/\lambda = 1{,}000$ km/s.

A photon emitted by the star in this wavelength range will be absorbed by some layer of the envelope at some distance from the star. After undergoing a number of local scatterings, which do not contribute any net momentum to the wind, the photon will preferentially be scattered backwards to the opposite side of the envelope where it will be reabsorbed by a line shifted toward the red by $c\,\Delta\lambda/\lambda = 2V$ relative to the transition which had produced the first absorption. The process is then repeated. In each one of these scatterings the photon will contribute net momentum to the wind. Our calculations show that the process can be repeated a number of times (between 5 and 20), before the photon eventually escapes outwards or falls back on the star where it is thermalized. Therefore the momentum imparted to the wind by this mechanism can be several (e.g. 5 to 20) times the luminosity in the wavelength range 200 Å – 500 Å divided by the speed of light. This is just what is required to produce the observed velocities in the winds of the hot stars.

It has to be stressed that this mechanism is only useful in accelerating the wind but it presupposes the existence of the mass-loss. In other words we have not yet explained how the mass-loss itself is produced.

I am convinced that in the coming years a concerted attack based on ultraviolet, visible and infrared observations will produce the evidence required by the theoreticians to solve the problem of mass-loss.

Fig. 4: *The Large Magellanic Cloud.*

PERSONNEL MOVEMENTS

STAFF

ARRIVALS

Europe

Raimund SCHULTZ, D, Driver/General Clerk, 16. 5. 1980
Gianni RAFFI, I, Software Engineer, 1. 7. 1980
Marie-Françoise BERNARD, F, Bilingual Secretary, 1. 9. 1980
Jean QUEBATTE, CH, Assistant Photographer, 1. 9. 1980
Claus MADSEN, DK, Photographer, 1. 9. 1980
Eduard STORTENBEEK, NL, Buyer, 1. 9. 1980
Charlie OUNNAS, F, Astronomical Applications Astronomer, 1. 10. 1980

Chile

Paul LE SAUX, F, Systems Analyst/Programmer, 1. 7. 1980
René NERI, F, Electromechanical Engineer, 1. 7. 1980

DEPARTURES

Walter GROEBLI, CH, Designer/Draughtsman (Mechanical), 30. 6. 1980
Bernard FOREL, F, Technical Draughtsman (Mechanical), 31. 7. 1980
Calixte STEFANINI, F, Head of Personnel, 31. 7. 1980
Gilles GOUFFIER, F, Accountant, 31. 7. 1980
Roy SAXBY, UK, Photographer, 31. 8. 1980
Alain PERRIGOUARD, F, Systems Programmer, 31. 8. 1980