JOINT DISCUSSION NO. 7

PHYSICS OF THE CHROMOSPHERE - CORONA-WIND COMPLEX AND MASS LOSS IN STELLAR ATMOSPHERES

(Commissions 10, 12, 29, 35, 36, 44)

Edited by D. H. Mihalas

Organizing Committee:

D. H. Mihalas and R. Bonnet (Co-Chairmen)
G. B. Brueckner, A. G. Hearn, Y. Kondo, H. Lamers,
G. Newkirk, T. P. Snow, R. N. Thomas,
A. B. Underhill, J. Ziolkowski

CONTENTS

JOINT DISCUSSION NO. 7

PHYSICS OF THE CHROMOSPHERE - CORONA-WIND COMPLEX AND MASS LOSS IN STELLAR ATMOSPHERES

CHROMOSPHERES, CORONAE, AND MASS LOSS IN STARS HOTTER THAN THE SUN

Theodore P. Snow, Jr.
Laboratory for Atmospheric and Space Physics and
Department of Astro-Geophysics,
University of Colorado
Boulder, Colorado 80309

Abstract

Reviews of the mass-loss characteristics of OB stars have been published recently, and the present review therefore emphasizes the A and F stars and very recent results on O and B stars. For the F stars, chromospheric indicators are present in the form of emission lines, seen in visible and ultraviolet wavelengths. Winds are present in A supergiants, but not in main sequence stars, although at least a few of the latter are X-ray sources, indicating the possible existence of coronae. Most OB supergiants are X-ray sources as well, indicating, along with the presence of super-ionization, that these stars have coronae. On the main sequence, the O stars and some B stars (including Be stars in many cases) have mass loss with highly-ionized species in the wind. The winds in the O and B stars are commonly variable. The mass-loss rates do not show a simple dependence on luminosity, contrary to the predictions for radiatively-driven winds.

I. INTRODUCTION

Evidence for mass loss in the O and B stars, particularly the supergiants, has been known for decades, and was systematically studied in the 1960's, first by the analysis of visible emission lines (e.g., Hutchings 1979 and references cited therein) and later through observations of ultraviolet P Cygni profiles (e.g., Snow and Morton 1976). In the past five years, the possibility that these hottest stars have coronae has been raised (Rogerson and Lamers 1975), and some of the current models, (reviewed by Cassinelli 1979a and by Cassinelli, Castor, and Lamers 1978), as well as very recent X-ray results, appear to bear this out.

While chromospheres and coronae in OB stars were not expected under the traditional assumption that these phenomena require the presence of convection in the outer layers, there was indirect evidence in the form of excess line broadening (Lamers 1974; de Loore 1970; Nariai 1969). Even consideration of line broadening leads to no

Patrick A. Wayman (ed.), Highlights of Astronomy, Vol. 5, 525–531.

https://doi.org/10.1017/S153929960000441X Published online by Cambridge University Press

expectation of chromospheres and coronae in A stars, however, since microturbulence, as derived from curve-of-growth analyses, is minimized for this spectral type. Spectroscopic and photometric indicators of temperature reversals for the A stars have been lacking as well, although controversial detections of emission lines or excess UV flux have occurred. For the F stars, chromospheres have been known for some time to exist, primarily due to observations of CaII H and K line emission, and these stars simply represent the high-temperature end of the sequence of "classical" chromospheres, driven by convection.

Comprehensive reviews of the observational data on winds in O and B stars have recently been published (Conti 1978; Cassinelli 1979a; Snow 1979; Hutchings 1979), and the reader is referred to these papers for summaries of the data through 1978. The present review will instead concentrate on very recent results for the OB stars and will summarize the evidence for chromospheres, coronae, and winds in A and F stars, which was not covered extensively by the earlier reviews.

The organization of this paper is by observational technique, starting with radio and then with visible and infrared results and progressing from there towards shorter wavelengths, with discussions of ultraviolet and then X-ray data. The final section summarizes the evidence for chromospheres, coronae, and winds as a function of spectral type, and then offers suggestions for further useful observations.

II. OBSERVATIONAL EVIDENCE

a. Radio Observations

Free-free scattering should produce excess continuum emission at long wavelengths from a star with an extended atmosphere. This shows up most strongly in the infrared (see Section b, below), but may also be sufficiently strong for detection at radio wavelengths. When possible, radio continuum measurements provide accurate measurements of mass-loss rates, because this emission originates at a large distance from the star, above the height where acceleration occurs, so that one need only know the terminal velocity. Unfortunately, it is very difficult to detect the radio emission from OB stars, and it has been done in only a few cases (Morton and Wright 1978; Abbott 1979), but development of new instruments such as the VLA will help.

b. Visible and Infrared Techniques

The traditional chromospheric indicator, CaII emission, has been observed for stars as hot as F0 (Warner 1966, 1968), but with few exceptions, does not appear in A stars, and the OB stars are too hot to have significant CaII even in their photospheres. Emission in Vega (A0V) due to the K line of CaII was once reported (Linsky *et. al.*, 1973), but could not be confirmed by later observers (Friere *et. al.*, 1977).

Similarly inconclusive were observations of infrared lines of OI and CaII, reported to be in emission, again in Vega, by Johnson and Wisniewski (1978). Later work with different observing techniques failed to detect the emission (Barker et. al. 1978; Griffin and Griffin 1978). Hence the visible and infrared spectroscopic evidence for chromospheres in stars hotter than F0 is at best controversial.

Infrared photometry provides a separate basis for hypothesizing the presence of chromospheres in some early A stars, which were reported to have 20μ excesses (Morrison and Simon 1973).

For the hot stars, visible-wavelength spectroscopy has revealed several classes of emission-line objects presumed to have extended atmospheres, and for supergiants at least, these data clearly indicate the presence of winds, through the presence of velocity-excitation and velocity-ionization correlations. The visible-wavelength evidence for winds in early stars has recently been reviewed by Hutchings (1979) and by Conti (1978).

Infrared photometry also can be used to detect the presence of extended atmospheres which produce infrared excesses through free-free scattering. Measurements of the excess flux distribution, coupled with some knowledge of the velocity law, can be used to estimate mass-loss rates, as was recently done for a number of OB supergiants by Barlow and Cohen (1977).

c. Ultraviolet Results

The discovery of high-velocity winds in OB supergiants occurred very quickly (Morton 1967) with the advent of ultraviolet rocket-borne spectroscopy, and a wealth of data on the phenomenon has accumulated since, through the development of sophisticated satellite observatories such as *Copernicus* and *IUE*. Observational results have been summarized recently, by Snow and Morton (1976), Snow (1979), Conti (1978), and Snow and Linsky (1979; the latter review covers late-type stars as well). The various observational studies of wind phenomena have been aimed primarily at categorizing the stellar parameters associated with the presence of winds. In addition to this, some analyses of mass-loss rates have been made based on ultraviolet line profiles (e.g., Lamers and Morton 1976), and recently variability in the winds has begun to be studied (e.g., Snow, Wegner, and Kunasz 1979, and references cited therein). In this regard, data from *IUE* on one O supergiant (α Cam) have revealed a gradual acceleration in the terminal velocity (de Jager et. al., 1979).

Comprehensive studies of mass-loss rates important for stellar evolution theories are also underway (Conti and Garmany 1979; Lamers, Gathier, and Snow 1979).

A very significant result has recently appeared, in the paper by Conti and Garmany (1979), which is based in IUE data. It was found that mass-loss rate is not a simple function of luminosity, as had been predicted by the theory of radiatively-driven winds, and had appeared to be confirmed by earlier *Copernicus* data (Snow 1979). Conti and Garmany found instances of stars with nearly identical basic properties (i.e., in the same location in the H-R diagram), but with mass-loss rates that differed by as much as two orders of magnitude. While there are some uncertainties due to the difficulty of determining the ionization balance in the wind, it seems unlikely that these uncertainties are sufficiently large to overcome the apparent disparity. Evidently some factor other than luminosity creates the outflow and hence determines the mass-loss rate, although once started, the flow may be accelerated by radiation pressure.

In the O and B stars (at least the *early* B stars), ultraviolet spectroscopy reveals the presence of super-ionized species in the winds, i.e., ions appear in the outflowing material that cannot be produced by the photospheric radiation field (Lamers and Snow 1978), and therefore signify the presence of a corona. Such excess ionization does not appear in the A supergiants, although these objects do have winds (Snow and Morton 1976; Praderie, Talavera, and Lamers 1979), as evidenced by shifted resonance absorption lines. No shifted absorption lines, emission, or superiorization appears in the ultraviolet spectra of A dwarfs, so again there is no clear evidence of chromospheres or coronae, or even of winds, in these objects.

For the F stars, early Copernicus data (Evans, Jordan, and Wilson 1974, 1975) and recent IUE data (Böhm-Vitense and Dettman 1979) reveal emission due to MgII and several other species (e.g., HeII, CII, CIV, OI, SiII, SiIV) with a variety of ionizations, confirming that chromospheres and coronae can exist throughout this spectral class. The effective temperature below which chromospheres and coronae begin to appear is linked to the region in the H-R diagram where convection occurs (Böhm-Viteuse and Dettman 1979). Ultraviolet chromospheric emission lines in high-luminosity objects do not extend as far to the left in the H-R diagram as they do for main sequence objects.

Hence ultraviolet data show that O and early B stars have winds and coronae, while A supergiants have winds only, with no evidence for chromospheric or coronal temperatures. The A dwarfs have no evidence for winds or coronae, while F stars show ultraviolet chromospheric emission, the latter stars probably representing the high-temperature end of the sequence of objects with classical chromospheres driven by convection.

d. X-ray Observations

One model for the super-ionization in O star winds involves photoionization due to soft X-rays from a hot corona (Cassinelli and Olson 1979 and references cited therein). The X-ray detectors on ANS and HEAO-1, as well as earlier experiments, failed to detect OB stars, but the limits were just consistant with these models. Now the Einstein Observatory (HEAO-2) has detected soft X-ray emission from numerous O and B supergiants (Harnden et. al. 1979; Cassinelli 1979b), in good agreement with the models. It thus appears quite likely that OB supergiants have hot ($T{\sim}10^7K$) coronae. If Einstein has sought X-ray emission from OB dwarfs, the results are not known to this author.

For the A stars, the X-ray data provide the best evidence to date for the existence of coronae, but even in this case uncertainties persist. A few A dwarfs have been reported as soft X-ray sources, either on the basis of ANS (Mewe et. al. 1975; den Boggende et. al. 1979), HEAO-1 data (Lampton et. al. 1979), or rocket experiments (Topka et. al. 1979), but controversy exists in each case either over either the identification of the true source (i.e., whether the A star or a white dwarf companion emits the X-rays), or its reality. Very recently an Ap star (ϕ Her) was identified as a source in HEAO-1 data (Cash, Snow, and Charles 1979), but no others have been found yet, and the possibility of a white dwarf companion in the single case reported cannot be ruled out. Further studies of A dwarfs are under way with HEAO-2 (Snow and Cash 1980).

III. SUMMARY AND SUGGESTIONS

The evidence for chromospheres, coronae, and winds may now be summarized by spectral class:

O Stars: Winds are required to explain both visible and ultraviolet line profiles, as well as the presence of infrared and radio continuum emission. The presence of super-ionization, seen in the ultraviolet spectra, indicates that coronae are present, and this is borne out by recent detections of soft X-ray emission from supergiants. Apparently, O stars of all luminosity classes have coronae, although the author is not aware of X-ray detections of main sequence stars. The mass-loss rates in O supergiants do not depend in a simple way on luminosity, and may be variable.

B Stars: All B supergiants have winds, as do the early B dwarfs, as shown by ultraviolet line profiles. Variability is common. The early B supergiants appear to have coronae, displaying super-ionization and X-ray emission, but the late B objects may not.

A Stars: Winds exist in A supergiants, but no definite evidence for winds or chromospheres in dwarfs has been found in infrared, visible, or ultraviolet spectra. Some A dwarfs have been identified as X-ray sources, but there are uncertainties in attributing these identifications to the A stars, rather than to possible companions. Some early A stars have infrared excesses possibly indicative of extended atmospheres.

https://doi.org/10.1017/S153929960000441X Published online by Cambridge University Press

F Stars: Main sequence stars as hot as F0 show CaII emission, and MgII and other ultraviolet emission lines (including those of highly-ionized species such as SiIV and CIV) are seen for F2 and cooler objects. The F stars appear to represent the high-temperature end of the sequence of late-type stars with chromospheres and coronae driven by photospheric correction.

The most obvious and important areas for continued observational work include the derivation of mass-loss rates for larger numbers of stars, further studies of variability in the winds, and more extensive searches for soft X-ray sources among early-type stars. The mass-loss rates are needed to test further the theories of radiatively-driven winds, and to look for correlations between these rates and stellar parameters other than luminosity. Accurate mass-loss rates are needed by stellar evolution theorists as well. Better data on variability in the winds, besides helping to refine knowledge of mass-loss rates by determining the degree to which they vary, may also provide important clues to the wind origins and stability. The acquisitions of more extensive X-ray data, in particular with the Einstein Observatory, will help to settle fundamental questions about the nature of the winds and the existance of coronae, particularly for the A stars.

Preparation of this review has been supported in part by National Aeronautics and Space Administration grants NSG5300 and NSG5355 to the University of Colorado.

REFERENCES

Abbott, D. C. 1979, Private Communication
Barker, E. S., Lambert, D. L., Tomkins, J., and Africano, J. 1978, Pub.A.S.P., 90. 514
Barlow, M. J. and Cohen, M. 1977, Ap.J, 312. 737
Böhm-Vitense, E. and Dettman, T. 1979, Preprint
Cash, W. C., Snow, T. P., and Charles, P. 1979, Apt. J. (Letters), in press
Cassinelli, J. P. 1979a, Ann. Rev. Astr. Ap., 17, in press
Cassinelli, J. P. 1979b, Private Communication
Cassinelli, J. P., Castor, J. I., and Lamers, H. J. G. L. M., 1978, Pub. A.S.P., 90. 476
Cassinelli, J. P., and Olson, G. L., 1979, Ap. J. 229, 304
Conti, P. S. 1978, Ann. Rev. Astr. Ap., 16, 371
Conti, P. S. and Garmany, K. D., 1979, Ap. J., submitted
de Jager, C., Lamers, H. J. G. L. M., Machetto, F., and Snow, T. P. 1979, Astr. Ap. , submitted
de Loore, C., 1970, Ap. Space Sci., 6 60
den Boggende, A. J. F., Mewe, R., Heise, J., Brinkman, A. C., Gronenschild, E. H. B. M., and Schrijver, J., 1978, Astr. Ap. 67. L29
Evans, R. G., Jordan, C., and Wilson, R., 1974, Nature. 253. 504
Evans, R. G., Jordan, C., and Wilson, R., 1975 Mon. Not. R.A.S. 172, 585

Friere, R. Czarny, J., Felenbok, P., and Praderie, F., 1978 Astr. Ap., 68, 89
Griffin, R. and Griffin, R. 1978, Pub. A.S.P., 90, 518
Harnden, F. R., Branduardi, G., Elvis, M., Gorenstein, P., Grindlay, J., Pye, J. P., Rosner, R., Topka, K., and Viana, G. S., 1979, Ap. J. (Letters)
Hutchings, J. B., 1979, IAU Symposium 83, Mass Loss and Evolution in O Stars, ed. C. de Loore and P. S. Conti (Dordrecht; Reidel), pp. 3.
Johnson, H. L. and Wisniewski, W. Z., 1978, Pub. A.S.P., 90, 139
Lamers, H. J. G. L. M., 1974, Doctoral Dissertation, University of Utrecht
Lamers, H. J. G. L. M., Gathier, R. and Snow, T. P., 1979, in preparation
Lamers, H. J. G. L. M., and Morton, D. C., 1976, Ap. J. Suppl., 32, 715
Lamers, H. J. G. L. M., and Snow, T. P., 1978, Ap. J., 219, 504
Lampton, M., Tuohy, I., Garmire, G., and Charles, P., 1979, X-ray Astronomy (COSPAR Reports), ed. W. A. Boity and L. E. Peterson (Oxford:Pregamon), p. 125
Linsky, J. L., Shine, R. A., Ayers, T. R., and Praderie, F. 1973, B.A.A.S., S, 3
Mewe, R., Heise, J., Gronenschid, E. H. B. M., Brinkman, A. C., Schrijver, J. and den Boggende, A. J. F., 1975, Ap. J. (Letters), 202, L67
Morrison, D. and Simon, T., 1973, Ap. J., 186, 193
Morton, D., C., 1967, Ap. J., 147. 1017
Morton, D. C. and Wright, A. E., 1978, Mon. Not. R.A.S., 182, 479
Naviai K. 1969, Ap. Space Sci., 3, 150
Praderie, F., Talavera, A., and Lamers, H. J. G. L. M., 1979, Astr Ap., submitted
Rogerson, J. B. and Lamers, H. J. G. L. M., 1975, Nature, 256, 190
Snow, T. P., 1979, IAU Symposium 83, Mass Loss and Evolution in in O Stars, ed. C. de Loore and P. S. Conti (Dordrecht:Reidel), pp. 65.
Snow, T. P. and Cash, W. C., 1980, in preparation
Snow, T. P. and Linsky, J. L., 1979 Proc. Conf. on Astr. Ap. from Spacelab, ed. P. L. Bernacca and R. Ruffini (Dordrecht:Reidel), pp. 645.
Snow, T. P. and Morton, D. C., 1976, Ap. J. Suppl., 32, 429
Snow, T. P., Wegner, G. A., and Kunasz, P. 1979, Ap. J., submitted
Topka, K., Fabricant, D., Harnden, F. R., Gorenstein, P. and Rosner, R., 1979, Ap. J., 229, 661
Warner, B., 1966, Observatory, 86, 82
Warner, B., 1968, Observatory, 88, 217

https://doi.org/10.1017/S153929960000441X Published online by Cambridge University Press