NASA CR-189314

IN-89-TM
175485
P.10

THE EVIDENCE FOR CLUMPY ACCRETION IN THE HERBIG Ae STAR HR 5999

M. R. Pérez
Astronomy Programs-CSC, IUE Observatory, NASA-GSFC, Greenbelt, MD 20771, USA

C. A. Grady
Applied Research Corporation, Landover, MD 20785, USA

and

P. S. Thé
Astronomical Institute "Anton Pannekoek", University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands

Abstract. Analysis of IUE high- and low-dispersion spectra of the young Herbig Ae star HR 5999 (HD 144668) covering 1978-1992 has revealed dramatic changes in the Mg II h and k (2795.5, 2802.7 Å) emission profiles, changes in the column density and distribution in radial velocity of accreting gas, and flux in the Lyα, O I and C IV emission lines, which are correlated with the UV excess luminosity. We also observe variability in the spectral type inferred from the UV spectral energy distribution, ranging from A5 IV-III in high state to A7 III in the low state. The trend of earlier inferred spectral type with decreasing wavelength and with increasing UV continuum flux has previously been noted as a signature of accretion disks in lower mass pre-main sequence stars (PMS) and in systems undergoing FU Orionis-type outbursts. Our data represent the first detection of similar phenomena in an intermediate mass ($M \geq 2\ M\odot$) PMS star. Recent IUE spectra show gas accreting toward the star with velocities as high as +300 km s^{-1}, much as is seen toward β Pic, and suggest that we also view this system through the debris disk. The absence of UV lines with the rotational broadening expected given the optical data (A7 IV, V sini=180± 20 km s^{-1}) for this system also suggests that most of the UV light originates in the disk, even in the low continuum state. The dramatic variability in the column density of accreting gas, is consistent with clumpy accretion, such as has been observed toward β Pic, is a hallmark of accretion onto young stars, and is not restricted to the clearing phase, since detectable amounts of accretion are present for stars with 0.5 Myr$< t_{age} <$ 2.8 Myr. The implications for models of β Pic and similar systems are briefly discussed.

Key words: pre-main sequence; variable; spectroscopy; accretion; HR 5999

1 Introduction

Recent studies of massive pre-main sequence (PMS) or Herbig Ae/Be (HAEBE) stars, probably the progenitors of systems like β Pic, have suggested that many of the IR, optical, and UV features of these systems are associated with large, viscously heated accretions disks with $M_{acc} \geq 10^{-7}$ M$\odot$ yr^{-1} (Hillenbrand et al. 1992, Blondel et al. 1992). This represents a significant departure from previous models which assumed, based on the presence of emission lines of species commonly seen in late-type star chromospheres, that most of the optical and UV spectral characteristics of HAEBE stars were produced in a chromosphere (c.f., Catala et al. 1984).

The irregular variable star HR 5999 (HD 144668, V856 Sco, CPD -38° 6373) is

(NASA-CR-189314) THE EVIDENCE FOR CLUMPY ACCRETION IN THE HERBIG Ae STAR HR 5999 (NASA) 10 p

N94-12915

Unclas

G3/89 0175485

one of the most studied massive PMS star at optical, UV and IR wavelengths. This star has shown quasi-periodic and random photometric and spectroscopic variabilities recently summarized by Tjin A Djie et al. (1989), Praderie et al. (1991) and Pérez, Webb and Thé (1992a). Three recent studies have suggested that many of the features of the circumstellar environment of HR 5999 can be accounted for by the presence of an optically thick accretion disk. Blondel et al. (1992) suggested the presence of such a disk as a result of their analysis of the extended Lyα emission around HR 5999, which is interpreted as formed by recombination of infalling matter onto the central source. Pérez et al. (1992a) have suggested instabilities in an accretion disk as the source of non-periodic photometric variability in the optical. More recently, Hillenbrand et al. (1992) have interpreted the infrared excess of HR 5999 in terms of a large, optically thick debris disk with a high accretion rate and a possible inner cavity.

Baade and Stahl (1989) extensively studied the photometric and spectroscopic variability of HR 5999, however, they barely mentioned that the Hα lines appeared in inverse Beals (1950) type III P Cygni profiles during the nights of June 7 and 8 in 1987. This immediately led us to pursue a monitoring of the UV spectral changes started on September 7, 1990, focused on the shape of the Mg II lines (2800 Å), which are being formed in more extended regions than Hα (up to 50 stellar radii). Our first observation confirmed the prediction that Mg II lines in HR 5999 are a good tracer of the dynamics in extended shells and/or bipolar flows by appearing as an inverse type III P Cygni profile, similar to Hα, indicating the increase of accretion phenomena in the line of sight. A more detailed report of the observations and analysis discussed here is published elsewhere (Pérez et al. 1993).

2 Relevant Observational Features of HR 5999

Among the massive PMS stars, HR 5999 is one of best studied objects; however, its photometric and spectroscopic behavior appears to be somewhat different from other objects in this class, such as AB Aur (for some researchers, this is the prototype of the HAEBE class), HD 163296, HD 104237, etc. Nevertheless, HR 5999 fits all three classification criteria of the PMS Ae and Be class defined by Herbig (1960), although is not in his original list of 26 members. In Table 1 and subsequent paragraphs, we have described some of the observational parameters of this star, as best known at this time.

In the following list, we have summarized some of the relevant properties and observational features of this star.

- Associated with the Lupus T3 star-forming cloud; embedded in nebulosity clearly visible on the POSS prints.
- The ratio of total to selective extinction, R_v=5.8 (Pérez et al. 1992a) is consistent with dust in the line of sight with a particle size distribution dominated

TABLE I
HR 5999 Observational Parameters

Spectral Type	T_{eff} (K)	log g	L ($L_\odot$)	v sini (km s^{-1})	R ($R_\odot$)	distance (pc)	M ($M_\odot$)	t_{age} (yr)
A5-7 III-IVe	7,800	3.5–4.0	133	180±20	6.4	270	3–3.5	5×10^5

by large grains and different significantly from that typical of the diffuse ISM (R_v=3.1).

- Variable intrinsic polarization in the optical ranging from 0.13–0.52% with a wavelength dependence consistent with dust (Thé et al. 1981).

- Spectroscopic and photometric variabilities from 1975–1985 are summarized by Tjin A Djie et al. (1989) and Praderie et al. (1991). Optical absorption lines due to singly ionized elements are particularly variable. Based on the variability detected in HR 5999, a qualitative model involving a corotating and slowly expanding region, surrounded by slowly rotating layers with higher expansion velocities is proposed by Praderie et al. (1991).

- Visual photometric variability and color changes have been observed in the last 20 years. This star does not show photometric indications of the "blueing" or "color reversal" effect detected in other massive PMS stars such as UX Ori, BF Ori, CQ Tau, etc. (Bibo and Thé 1991), however, spectral *blue* and *red* outbursts were found in this dataset (Pérez et al. 1992a). Short-duration (8-10 days) enhancements in the luminosity of the star, randomly located in time, have been interpreted as evidence for accretion instabilities.

- The photosphere is only visible at few optical windows. The stellar projected rotation rate is inferred to be 180±20 km s^{-1} based on broadening of Mg II 4481 Å. Photospheric absorption is not detectable at Na I D and Ca II lines (Lagrange-Henri al. 1990). Photospheric features are not seen in the UV from 2580–3000 Å (Pérez et al. 1993).

- Blondel et al. (1989) find, in the first 7 years of IUE data, a tendency for Fe II and other absorption features to have smaller equivalent widths when the star is fainter.

- Hα and Mg II have P Cygni type III (emission with central absorption reversal) profiles. Both emission profiles are variable and prior to 1986, published data indicate that V<R. Beginning in June 1987 (Baade and Stahl 1989) and continuing through 1991, V>R. Recent optical and IUE spectra (August and September 1992) present V<R.

- Hillenbrand et al. (1992) classify the IR excess for this star as consistent with an optically thick accretion disk extending from 6 $R_\star < r <$ 23 AU with an accretion rate of 1×10^{-6} M$\odot$ yr^{-1}.

- Ly α emission peaking at 850 km s^{-1} and with a FWHM of 1240 km s^{-1} is seen at an epoch when the star is optically bright (Blondel et al. 1992). If interpreted as originating in a bipolar flow, the inferred mass accretion rate is 6.8×10^{-7} M$\odot$ yr^{-1}.

3 Recent Ultraviolet Observations

After September 1990 several new IUE observations in high- and low-dispersion with both the long- (LW) and short-wavelength (SW) cameras have been carried out in order to continue the monitoring of this star started in 1978, during the early days of the IUE spacecraft. Some of the relevant results from the high-dispersion data have been reported by Blondel et al. (1989). We briefly summarized some of the results obtained from the archival and recent observations.

3.1 The UV continuum variability

A striking feature of HR 5999 in the optical is the pronounced photometric variability. As shown in Figure 1, the continuum exhibits significant variability down to at least 1450 Å. In the longer wavelength portion of the spectrum near the Mg II resonance doublet, the continuum luminosity can be grouped into a UV-bright state and a UV-faint state, with up to a magnitude difference in flux levels between the states. The UV bright state at 2815 Å has been observed only for V(FES)<7.0 (this V magnitude has been calculated from the IUE Fine Error Sensor (FES) using the calibration by Pérez and Loomis 1991). At 1630 Å, faint and bright states are observed, but the association with V(FES) is less apparent. UV-bright states are observed down to V(FES)=7.46, while fainter spectra are observed over the same range as at 2815 Å. The 1450 Å data exhibit significant variation which does not appear correlated with the continuum flux at longer wavelengths. In all spectra, even those obtained in the UV-faintest states observed to date, the IUE spectra provide convincing evidence for a continuum UV excess compared to similarly exposed A5-A7 standard star spectra down to Lyα.

3.2 Correction for interstellar and circumstellar extinction

It has been known for some time that the extinction law towards HR 5999 is quite anomalous (Thé and Tjin A Djie 1978, Thé et al. 1981, Hecht et al. 1984), typical of other active star-forming regions, such as Orion. Preliminary estimates of the ratio of total to selective extinction, $R_v = \frac{A_v}{E(B-V)}$, accounting for both the foreground and circumstellar extinctions, were between 4 and 5. Our trial-and-error fit of the unreddened optical fluxes to the Kurucz (1991) models indicated an R_v value of $\sim$ 5.5–5.7. The latest R_v value based on Strömgren photometric data

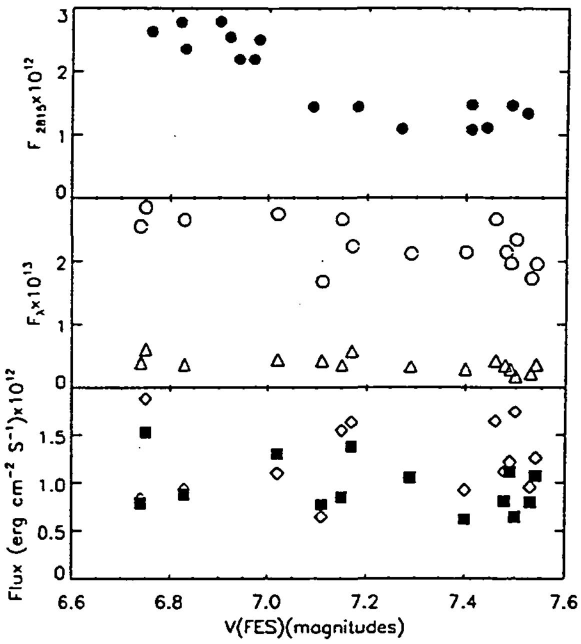

Fig. 1. UV photometric variability in HR 5999 of the observed fluxes as a function of the derived visual magnitude V(FES). Continuum variability at 2815 Å (filled circles), 1620 Å (open circles), 1450 Å (triangles) is shown. Net observed emission fluxes for C IV (filled squares) and O I (diamonds) are also indicated.

derived from 282 data points covering 7 years of monitoring, is 5.8 (Pérez et al. 1992a). This value is intended to be an average since R_v becomes smaller when the star gets brighter as acknowledged by Thé et al. (1985) and Pérez et al. (1992a). By properly correcting for extinction the low-dispersion data we found that even in the UV-faint state, the continuum flux mimics a A5 III at these wavelengths with detectable excess shortward of 1600 Å and longward of 2600 Å.

A trend of inferred spectral type shifting to earlier types with decreasing wavelength, larger UV excesses during episodes of high optical luminosity, and a flux distribution which is not consistent with a single-temperature stellar model, has previously been observed in lower mass pre-main sequence (PMS) stars, particularly in stars undergoing FU Orionis-type outbursts (Hartmann and Kenyon 1985). These phenomena have been interpreted as evidence for the presence of emission from an optically thick accretion disk and boundary layer. Our data provide the first detection of similar phenomena in a more massive protostar. The extent of the UV excess, even in the faintest UV spectra obtained to date is such that we would not expect to detect the stellar photosphere.

3.3 The emission lines

The spectrum of HR 5999 shortward of 1600 Å is rich in emission lines from species commonly associated with chromospheres in late-type stars. Both O I

(1320 Å) and C IV (1550 Å) exhibit significant variation in net emission fluxes and in the velocity range covered by the emission. The net fluxes and velocity widths are smaller in the UV-faint spectra compared to the UV-bright spectra. The UV-faint spectra show much less scatter than is observed in the UV-bright data. A distinctive feature of the C IV emission is the variability in the emission centroid. In general, the C IV emission characteristics show more scatter than O I, suggesting at least partial formation in a somewhat different region. Blondel et al. (1992) reached similar conclusions in a comparison of O I and Lyα in high dispersion IUE SW spectra.

3.3.1 Mg II emission

It is known that the shape of the Mg II lines in bright HAEBE stars there is a smooth progression of profiles ranging from well-developed type III P Cyg (Pérez et al. 1992b) for the youngest to narrow absorption lines for the stars with more main sequence characteristics. For the truly PMS among the HAEBE sample, the Mg II profiles are unique when compared with B main sequence and Be classical stars and are generally the signature of accelerating winds in their extended disks (between 315 and 495 km s^{-1} in the case of the extreme object AB Aur, Praderie et al. 1986).

The Mg II profiles in HR 5999 are similar in shape when compared with the youngest members in the HAEBE class, but they are also substantially narrower. It is believed that this is due to the viewing stellar geometry, nearly edge-on, and due to the fact that a part of the Mg II lines are probably produced in the bipolar outflows. The suggestion that this star is seen almost edge-on comes from its observed high rotational velocity, $v\ sin\ i$=180$\pm$20 km s^{-1} (Tjin A Djie et al. 1989, $\sim$ 66% of its break up velocity), its large infrared excesses (E(V-L)=3.2 mag) which in turn should produce high UV extinction ($1.2\leq A_{2800} \leq 2.2$ mag for R_v=5.8, according to Pérez et al. 1992a), however, the Mg II, C IV, Si IV emission lines for example, appear strong and relatively unaffected by changes in extinction indicating that the emission volume generating these infrared excesses are not isotropically distributed and they are likely to be confined to a disk.

All of the HR 5999 Mg II profiles obtained through 1985 have type III P Cygni profiles, despite being obtained at epochs of both high UV continuum flux (the 1979 data), and low continuum flux (all intervening spectra). When IUE observations resumed in September 1990, the character of the Mg II profile had changed drastically to type III *inverse* P Cygni profiles closely resembling the Hα profiles of Baade and Stahl (1989) (see Figure 2). Subsequent spectra obtained between 1991 and March 1992, also exhibit inverse P Cygni profiles, although not as extreme as the 1990 September observation. The Mg II emission was found to be more prominent relative to the continuum in spectra obtained during the low UV continuum state; the broad emission base extends to 300–350 km s^{-1}. However, our data suggest, that net emission is systematically higher in the high continuum state.

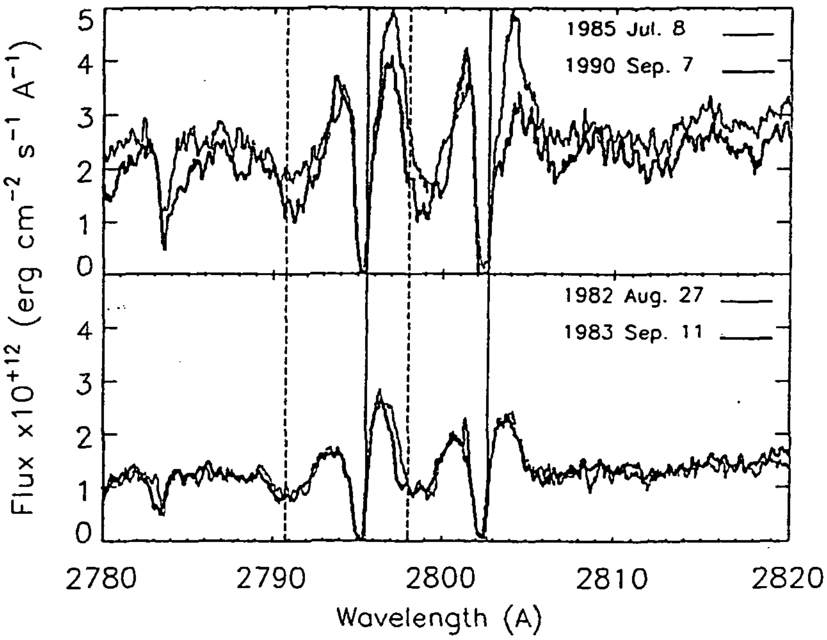

Fig. 2. Representative 2800 Å Mg II profiles for HR 5999. The upper panel shows two spectra obtained during the UV-bright state (LWP 6365, faint line; LWP 18717, bold line). Two spectra obtained during the UV-faint state are shown in the bottom panel (LWR 14026, faint line, and LWR 16769, bold line).

3.3.2 Singly ionized iron-peak species

The UV spectrum of HR 5999 is rich in absorption features to the ground configurations and excited levels of singly-ionized iron-peak elements (Blondel et al. 1989), and provides an opportunity to test our suggestion that the variability in the Mg II resonance profiles is due to variable column densities of accreting gas.

As noted by Blondel et al. (1989), strong absorption is present in the profiles of all of the lines of Fe II UV(1, 62, 63, 64, 68). The profiles from the UV(1) transitions are saturated over the velocity range -50 to 0 km s^{-1}. Longward of this saturated absorption the IUE spectra obtained prior to 1990 show absorption extending to approx. 300 km s^{-1}. From 1990 onward increased absorption from 0-300 km s^{-1}, and especially pronounced from 0-200 km s^{-1} is visible in all of the Fe II UV(1) lines (see Figure 3).

4 Comparison with β Pictoris

The singly ionized metal absorption profiles seen since 1990, with large column densities at low velocities and smaller column densities at progressively higher, positive velocities, are strongly reminiscent of the accreting gas profiles seen toward the proto-planetary system candidate β Pic. Both systems have circumstellar absorption profiles characterized by large column densities near the stellar

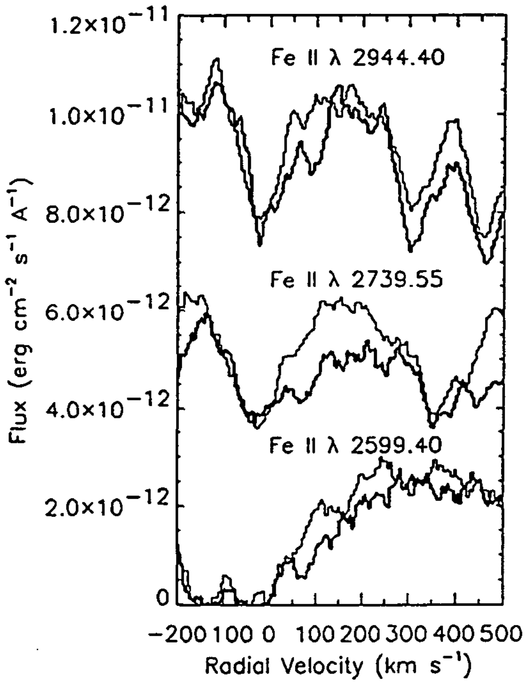

Fig. 3. Circumstellar Fe II absorption from 1985 July 8 (LWP 6365) and 1990 September (LWP 18717). The lines from top to bottom, 2944.4 Å (UV78), 2739.55 Å (UV 63) 2599.40 Å (UV1), demonstrate both the variability of the line-of-sight mass accretion rate during the UV-bright state and provide evidence for accreting gas with velocities as large as +300 km s^{-1}.

radial velocity, with decreasing absorption extending to high positive velocities in at least some spectra. Both systems exhibit high-density, high velocity gas of variable column density, absorption components in some spectra which are particularly prominent in the low velocity portion of the flow, and a trend for the FWHM of the components to increase with increasing radial velocity (see Boggess et al. 1991, Lagrange-Henri et al. 1992). The relative prominence of the accreting gas relative to the material closer to the inferred systemic velocity increases with increasing excitation potential, as does the suggestion of discrete absorption components, which are particularly prominent in the 1985 July 8 and 1990 September data. Similarly, the outflowing material observed in 1983 September 11, (LWR 16769) also becomes more prominent with increasing excitation potential. Similar behavior is observed in the accreting and outflowing gas toward β Pic (Bruhweiler et al. 1991, 1992, Boggess et al. 1991).

In the case of β Pic, higher S/N and resolution HST GHRS data have demonstrated that the excitation temperature of the accreting gas exceeds the stellar T_{eff}, and that the components have excitation temperatures above the temperature of the accreting gas at nearby velocities (Bruhweiler et al. 1992). The IUE data for HR 5999 suggest that the accreting gas in this, much younger system

($t_{age} \approx 5 \times 10^5$ year) with a significantly higher mass accretion rate, exhibits the same phenomena. The variability of the C IV net emission fluxes, compared with O I, may indicate the presence of C IV in absorption in the line-of-sight, since the UV-bright spectra with low C IV fluxes correspond to epochs with enhanced Mg II and Fe II absorption. If this assertion is supported by higher resolution UV spectra, such as can be provided by the HST, it will provide confirmation of the presence of collisionally ionized gas in the HR 5999 system. Detection of transient, outflowing material which is high density, and potentially collisionally ionized is a further point of similarity which must be accounted for in any model for accretion phenomena onto young, intermediate mass stars.

5 Conclusions

The UV data demonstrate, for the first time, that the photometric brightening of HR 5999 in the optical and UV is associated with increasing column densities of gas visible to 300–350 km s^{-1}. Sufficiently large amounts of material are involved that the UV continuum luminosity increases by one magnitude at 2800 Å. The photometric variability has previously been noted as a signature of accretion instabilities. Accretion signatures in this star have been independently detected by Hillebrand et al. (1992) and Blondel et al. (1992). If correct, the UV data suggest that the high velocity gas is perturbed into the inner portions of the accretion disk and the boundary layer by the same instabilities. Temporal variability in the high velocity, accreting gas is seen in the IUE data, although the spectra are sufficiently separated in time that we cannot infer the timescale for changes at high velocity. Previously such variability, termed clumpy accretion, has been reported for the HAEBE star R CrA (Graham 1992), BF Ori (Welty et al. 1992), and is characteristic of the accretion activity in older systems such as β Pic (Lagrange-Henri et al. 1992), 51 Oph (Grady and Silvis 1993), and HD 176386 (Grady et al. 1993). This certainly indicates that the timescale for the characteristic accretion signatures to occur are extended beyond 2.8 Myr (lower limit for age of 51 Oph and β Pic systems).

The optically thin cavity inferred from the IR excess flux distribution by Hillebrand et al. (1992), marks the location of the dust sublimation zone rather than a true void. Interior to this region, the UV data indicate the presence of optically thick gas. Progressive broadening of the line profiles with increasing ionization potential suggests that the majority of the gas seen in absorption near the system velocity is in predominantly Keplerian orbits, with small velocity components toward the star. Since this material is seen in all the UV data, as well as in the available optical spectra, the gas at the system velocity may correspond to the sublimation products of grains originally spiraling into the star via Poynting-Robertson drag. Exterior to this region, Thé and Molster (1993) has argued that this star is surrounded by proto-planetary clouds orbiting in the outer parts of the circumstellar disk, which are responsible for the optical variability.

Acknowledgements

Partial support for this study was provided by NASA Contract NAS 5-32059 to the Applied Research Corporation, and by NASA Contract NAS 5-31841 to Computer Sciences Corporation. Computing resources were provided by the IUE Regional Data Analysis Facility at NASA/GSFC.

References

Baade, D., Stahl, O. 1989, A&A, 209, 255.

Beals, C. 1950, Publ. Dom. Astrophys. Obs., 9, 1.

Bibo, E.A., Thé, P.S. 1991, A&AS, 89, 319.

Blondel, P.F.C., Tjin A Djie, H. R. E., Thé, P.S. 1989, A&A, 80, 115.

Blondel, P.F.C., Talavera, A., Tjin A Djie, H.R.E 1992, A&A, (in press).

Boggess, A., Bruhweiler, F.C., Grady, C.A., Ebbets, D.C., Kondo, Y., Trafton, L.M., Brandt, J.C., Heap, S.R., 1991, ApJ 377, L49.

Bruhweiler, F.C., Kondo, Y., Grady, C.A. 1991, ApJ 371, L27.

Bruhweiler, F.C., Lyu, H.-S., Boggess, A., Kondo, Y., Grady, C.A. 1992, ApJ (in press).

Catala, C., Kunasz, P.B., Praderie, F. 1984, A&A, 134, 402.

Grady, C. A., Silvis, J.M.S. 1993, ApJ, 402, L61.

Grady, C.A., Pérez, M.R., Thé, P.S. 1993, (this proceedings).

Graham, J.A. 1992, Pub. A.S. Pac. 104, 479.

Hartmann, L., Kenyon, S.J. 1985, ApJ, 299, 462.

Hecht, J.H., Holm, A.V., Ake III, T.B., Imhoff, C.L., Oliversen, N.A., Sonneborn, G. 1984, in Future of Ultraviolet Astronomy based on Six years of IUE Research, Nasa Conference Publication, No. 2349, p. 318.

Herbig, G. H. 1960, ApJS, 4, 337.

Hillenbrand, L.A., Strom, S.E., Vrba, F.J., Keene, J. 1992, ApJ, 397, 613.

Kurucz, R.L. 1991, in Precision Photometry: Astrophysics of the Galaxy, Davis Philip, A.G., Upgren, A.R., Janes, K.A. (eds.) (Schenectady, N.Y.:: L. Davis Press).

Lagrange-Henri, A.M., Ferlet, R., Vidal-Madjar, A., Beust, H., Gry, C., Lallement, R. 1990, A&A Suppl. Ser. 85, 1089.

Lagrange-Henri, A.M. et al. 1992, A&A, (in press).

Pérez, M. R., Webb, J., Thé, P. S. 1992a, A&A, 257, 209.

Pérez, M. R., Imhoff, C. L.. Thé, P. S. 1992b, Bull. A.A.S., 23, No.4, 1374.

Pérez, M. R., Loomis, C. 1991, Record of the IUE Three Agency Coordination Meeting (NASA/ESA/SERC), Nov. 19-21, 1991 at GSFC, F-13.

Pérez, M. R., Grady, C. A., Thé, P. S. 1993, A&A, (in press).

Praderie, F., Simon, T., Catala, C., Boesgaard, A. M. 1986, ApJ, 303, 311.

Praderie, F., Catala, C., Czarny, J., Thé, P. S., Tjin A Djie, H. R. E. 1991, A&A, 89, 91.

Thé, P.S., Tjin A Djie, H.R.E. 1978, A&A, 62, 439.

Thé, P.S., Molster, F.J. 1993, (this proceedings).

Thé, P.S., Tjin A Djie, H.R.E., Bakker, R.s, Bastiaansen, P.S., Burger, M., Cassatella, A., Fredga, K., Gahm, G.F., Liseau, R., Smyth, M.J., Viotti, R., Wamsteker, W., Zeuge, W. 1981, A&AS, 44, 451.

Thé, P.S., Tjin A Djie, H.R.E., Brown, A., Catala, C., Doazan, V., Linsky, J.L., Mewe, R., Praderie, F., Talavera, A., Zwaan, C. 1985, Irish AJ, 17, 79.

Thé, P.S. et al. 1981, A&AS, 44, 451.

Tjin A Djie, H.R.E., Thé, P.S., Andersen, J., Nordstrom, B., Finkenzeller, U., Jankovics, I. 1989, A&AS, 78, 1.

Welty, A.D., Barden, S.C., Huenemoerder, D.P., Ramsey, L.W. 1992, AJ, 103, 1673.