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# ON THE NATURE OF MWC 349

L. HARTMANN, D. JAFFE, AND J. P. HUCHRA
Harvard-Smithsonian Center for Astrophysics
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## ABSTRACT

Line profile observations of MWC 349 confirm the suggestion of Olnon that the compact H II region surrounding the star is a stellar wind. The broad wings on Hα are caused by electron-scattering redistribution; the appreciable Thomson optical depth in the wind indicates that the photosphere of the star is extended. The terminal velocity of the wind is $\sim 50$ km s$^{-1}$, extremely slow for mass ejection from an early-type star. It is suggested that the slow wind and extended photosphere can be reconciled with the radiatively driven wind theory of Castor, Abbott, and Klein if MWC 349 has a low effective surface gravity, possibly because the star is overluminous for its mass.

*Subject headings:* stars: emission-line — stars: individual

## I. INTRODUCTION

The nature of the peculiar object MWC 349 has been the subject of controversy in recent work. Greenstein (1973) and Kuhi (1973) analyzed MWC 349 as a normal early-type star surrounded by a compact H II region. Thompson *et al.* (1977) described spectral peculiarities which led to a different picture. These authors found a de-reddened optical continuum spectrum $F_\nu \propto \nu^{1/3}$, which is much too flat for a hot main-sequence star capable of producing the necessary amount of ionizing photons, and that excess optical flux relative to the stellar Lyman continuum flux is present. From these results Thompson *et al.* (1977) concluded that a disk component dominates the optical emission. However, this analysis has been challenged by Brugel and Wallerstein (1979) because of contamination of the continuum observations by a nearby star.

The nature of the compact H II region around MWC 349 is an aspect of this source which has been neglected for the most part in previous analyses. In this paper we report line profile observations which confirm the suggestion of Olnon (1975) that the H II region is a stellar wind. The remarkable nature of this wind has important consequences for the interpretation of the nature of the underlying source.

## II. OBSERVATIONS

Spectra of MWC 349 were taken at Mount Hopkins Observatory with the 1.5 m telescope, using the intensified Reticon detector (Davis and Latham 1979). The MHO medium-dispersion spectrograph produced spectra with resolutions $\sim 5$ Å and $\sim 2.5$ Å. The echelle spectrograph was used to obtain line profiles of Hα and the [N II] lines at λ6548, λ6584 with a resolution $\sim 0.25$ Å, and of He I λ5876 and the Na I D lines at a resolution $\sim 0.20$ Å. The slit sizes on the sky were $3''.6 \times 12''.4$ at low dispersion and $1'' \times 5''.5$ for the high-dispersion spectra.

The most striking aspect of the low-dispersion spectra is the broad wings on Hα (cf. Herbig 1972). In Figure 1 we display the Hα profile data from two different nights in 1979 June, folded assuming central symmetry, along with a fit to be discussed below. These data were taken with a neutral density = 2 filter in order to avoid saturation and have not been corrected for the instrumental profile. This does not affect the wing shape in any event.

The equivalent widths of Hα and λ5876 on these nights were $W_\lambda = 735$ Å and 26.7 Å, respectively; a lower-dispersion spectrogram taken in 1978 November yields $W_\lambda = 770$ Å, 33.4 Å, and 71.7 Å for Hα, λ5876, and Hβ. The Hα and λ5876 equivalent widths, considering the difference in resolution, therefore do not vary within our accuracy.

Brugel and Wallerstein (1979) found an equivalent width of 1200 Å for Hα. The discrepancy may be the result of some continuum contamination from a nearby star $\sim 2''$ distant. This contamination will not affect the data in Figure 1, which have had the continuum subtracted to yield the net emission profile. Any possible Hα emission of the nearby star is relatively weak (Brugel and Wallerstein 1979).

In Figure 2 we present one of several echelle spectra obtained, displaying Hα and [N II]. The broad wings of Hα observed at low dispersion are confirmed, and a deep central reversal from self-absorption, which is only suggested by the 2.5 Å resolution data, is seen to be blueshifted from the line's center of symmetry by $\sim -15$ km s$^{-1}$. The [N II] λ6584 line is broad, with an FWHM of 96 km s$^{-1}$, and shows no evidence of wings.

The He I λ5876 and Na I λλ5890, 5896 lines are displayed in Figure 3. Both lines show absorption central reversals; λ5876 is blueshifted by the same

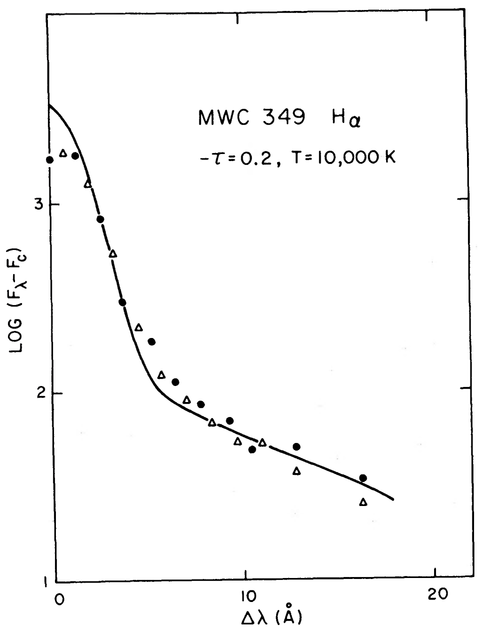


FIG. 1.—The Hα profile of MWC 349 observed at 2.5 Å resolution, with no correction for instrumental profile. The ordinate is the logarithm of the flux minus the continuum, in arbitrary units. Open triangles and filled circles represent data taken on 2 different nights, folded assuming central symmetry. The solid line is a calculation of the effects of an electron-scattering cloud of $\tau = 0.2$ on a theoretical Hα profile. The unscattered Hα line is approximated by a Gaussian profile with the same width as observed from the high-dispersion echelle spectrum. The scattered profile was then convolved with a Gaussian approximating the instrumental profile. Changes in the assumed unscattered line and instrumental widths affect the core of the calculated profile, but do not disturb the far scattering wings.

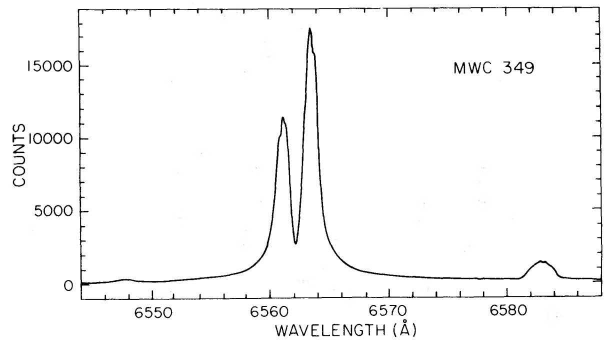


FIG. 2.—The echelle spectrum of MWC 349 showing Hα and [N II]. The central reversal of Hα is blueshifted by $\sim 15$ km s$^{-1}$ from its center of symmetry.

amount as Hα, $\sim -15$ km s$^{-1}$, with a FWHM of 130 km s$^{-1}$. The emission widths of the Na D are $\sim 110$ km s$^{-1}$; however, a precise estimate is uncertain because of the absorption. Similarly, analysis of the Na central absorption velocity shift is made difficult by the likelihood of significant interstellar absorption and by night-sky emission at line center. The amount of absorption is roughly consistent with the Na I equivalent width toward VI Cygni No. 12, a star with a comparable $E_{B-V}$ (Souza 1979).

## III. LINE PROFILE ANALYSIS

The standard model of the emission region of MWC 349 was introduced by Olnon (1975), who explained both the radio spectrum $F_\nu \propto \nu^{0.69}$ and the angular diameter with a density law $N \propto r^{-2.1}$, for $T \approx 1 \times 10^4$ K, $N_0 R_0^{\,2.1} = 0.9$ pc$^{2.1}$ cm$^{-3}$, and $D = 2.1$ kpc. Olnon suggested that this density law was the result of expansion at constant velocity. Harvey, Thronson, and Gatley (1979) have shown that the spectrum has a $\nu^{0.6}$ dependence for wavelengths longer than 100 μm (at shorter wavelengths, dust emission dominates), implying that the $r^{-2}$ density law holds over several decades in radial distance. With this density distribution, hydrogen and helium recombination lines are preferentially formed close to the star, while the [N II] lines, collisionally de-excited for $N > 7.8 \times 10^4$ cm$^{-3}$ (Osterbrock 1974), are formed much further away. The similarity of the [N II] and λ5876 line widths demonstrates that the suggestion of expansion at nearly constant velocity is correct.

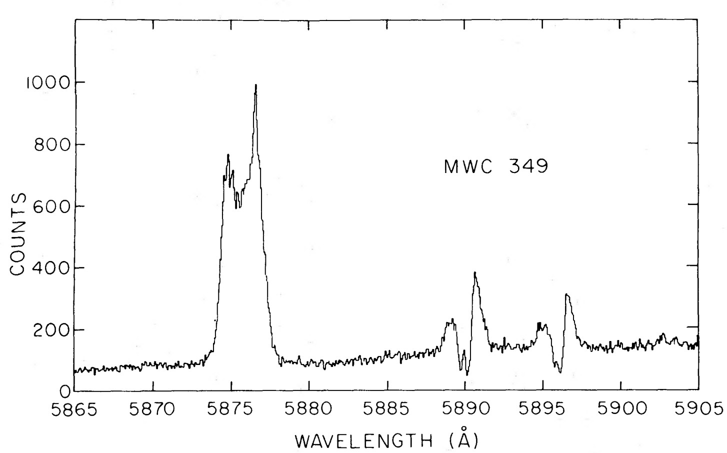


FIG. 3.—The echelle spectrum of He I λ5876 and Na I D in MWC 349. Night sky emission may contaminate the central absorptions of Na D.

Adopting $R_0 = 3.1 \times 10^{16}$ cm, which corresponds to the 5 GHz equivalent uniform disk angular diameter at a distance of 2.1 kpc, we find $N_0 = 1.4 \times 10$ cm$^{-3}$ from $N_0 {R_0}^{2.1} = 0.9$ cm$^{-3}$ pc$^{-2.1}$. Then, assuming $N \propto r^{-2}$, we may express emission measures and optical depths in terms of $X_1 \equiv R_1/R_0$, the scaled inner cutoff radius of the H II region, with the outer boundary at infinity.

The emission measure can then be written as

$$\mathrm{EM} = \frac{4\pi {N_0}^2 {R_0}^3}{X_1} = \frac{7.34 \times 10^{58}\ \mathrm{cm}^{-3}}{X_1}, \qquad (1)$$

and the electron-scattering optical depth is

$$\tau = \frac{N_0 R_0 \sigma_{\mathrm{T}}}{X_1} = \frac{2.89 \times 10^{-4}}{X_1}, \qquad (2)$$

where $\sigma_{\mathrm{T}}$ is the Thomson scattering cross section. Thompson *et al.* (1977) estimated $\mathrm{EM} \approx 2 \times 10^{61}$ cm$^{-3}$. This implies $X_1 = 3.67 \times 10^{-3}$, $R_1 = 1.14 \times 10^{14}$ cm, $N_1 = 1.04 \times 10^9$ cm$^{-3}$, and $\tau = 0.079$. The substantial electron-scattering optical depth calculated in this way strongly suggests that electron-scattering redistribution causes the broad wings on the H$\alpha$ line.

The suggestion of electron-scattering wings can be tested by comparing the observed line profile with a theoretical profile. The fraction of the source line emission that is scattered then yields an independent estimate of the electron-scattering optical depth. The relation between the amount of scattered flux and $\tau$ is geometry dependent. Mathis (1970) gives formulae for the fraction $f$ of the total line radiation which has undergone scattering from a spherical distribution of electrons. When the original emission comes from a central point source, $f = (1 - e^{-\tau})$. With a uniform distribution of emission, $f \approx 1 - 0.75[1 - \exp(-4\tau/3)]/\tau$. From the observed line profile shown in Figure 1 we estimate $f \approx 0.2$ by comparing the core and wing fluxes; then from the above formulae, $\tau(\mathrm{point}) \approx 0.22$ or $\tau(\mathrm{uniform}) \approx 0.35$. Since hydrogen emissivity has an $N^2$ dependence, the emission will be concentrated interior to the bulk of the scattering, so the point source geometry is more appropriate.

In Figure 1 we show a theoretical profile for a spherical electron-scattering cloud computed in the optically thin limit. The calculation assumes a Gaussian profile for the point source H$\alpha$ line, with a FWHM estimated from the echelle spectrum; the result is convolved with a Gaussian approximation to the instrumental profile. The profiles agree fairly well for $\tau \approx 0.2$ and $T = 10^4$ K. The principal uncertainty is the treatment of self-absorption in H$\alpha$. If we assume that the profile "before absorption" is similar to [N II], then the self-absorption reduces the H$\alpha$ emission by about a factor of 2. From this we estimate an uncertainty of a factor of $\sim 2$ in $\tau$.

Calculations for $\lambda 5876$ with the same optical depth indicate that the wings will be far less apparent than in the case of H$\alpha$. The latter line appears intrinsically broader, which increases the wing visibility, and the relative continuum strength is much lower, revealing the wings more easily. We suggest that the greater half-width of H$\alpha$ is due to a larger line optical depth than for $\lambda 5876$, which traps line photons and makes electron scattering in the line-forming region important. There may be an indication of the $\lambda 5876$ wings in Figure 3, but we have not determined the instrumental profile sufficiently accurately to be certain.

With $\tau = 0.2$, equations (1) and (2) lead to $R_1 = 4.5 \times 10^{13}$ cm, $N_1 = 6.7 \times 10^9$ cm$^{-3}$, and $\mathrm{EM} = 5.1 \times 10^{61}$ cm$^{-3}$. This emission measure is consistent with the estimate of Thompson *et al.* (1977) considering the uncertainties in $\tau$ and the likelihood of departures from simple nebular analysis. The emission measure is also consistent with the infrared spectrum for $\lambda \gtrsim 100\ \mu$m; the IR spectrum for $\lambda \gtrsim 30\ \mu$m is dominated by dust emission (Harvey, Thronson, and Gatley 1979).

## IV. WIND ANALYSIS

The line profile observations reported here confirm Olnon's (1975) suggestion that the H II region is a stellar wind. The observations of line widths indicate substantial mass motions, which we interpret as expansion from the blueshift of the H$\alpha$ central absorption (Fig. 2). From our optical depth estimate of $\tau \approx 0.2$ at $R_1$ we conclude that the H II region has been traced back to nearly the stellar photosphere. It is unphysical to assume that a "hole" exists between $R_1$ and the photosphere, because the expansion time scale $R_1/V_\infty$, with $V_\infty \approx 50$ km s$^{-1}$, is only 0.3 yr. The mass that is lost therefore must be replenished continuously. We consider $R_1$ to be simply the minimum radius at which nebular approximations suffice; interior to this point, large line and continuum optical depths ($\tau > 0.2$) will reduce hydrogen emissivity, so that continuous mass loss does not violate emission measure estimates.

In order to understand the nature of the wind theoretically, it is necessary to estimate some basic parameters of the stellar source. We can compute approximate Zanstra temperatures from the observed line strengths, using the model atmosphere calculations of Hummer and Mihalas (1970) for $\log g = 4.0$. While MWC 349 is clearly not a normal main-sequence star, the results of such an analysis are roughly indicative of the appropriate temperature range. Using recombination coefficients from Osterbrock (1974), we find $T_{\mathrm{eff}} \approx 32{,}000$ K, 32,200 K, and 34,000 K for H$\alpha$, H$\beta$, and He I, respectively. These results assume that the dust is external to the gas, so that the continuum undergoes the same extinction as the line emission. This approximation seems reasonable in light of the concentration of the emission measure at distances of only $10^{14}$ cm from the star. We adopt $T_{\mathrm{eff}} \approx 35{,}000$ K, consistent with the absence of He II $\lambda 4686$. The estimated bolometric correction for this temperature is $\sim -3.3$ (Code *et al.* 1976). We set $A_V \approx 9.0$, which is a compromise between the line extinction value (8.7) of

Thompson *et al.* (1977) and the value of 9.3 derived assuming a $v^2$ continuum. The large extinction to MWC 349 and its position in the sky connect it with the highly reddened VI Cygni association at a distance of 2 kpc (Olnon 1975; Thompson *et al.* 1977). Adopting $D = 2$ kpc implies $M_{\rm bol} \approx -10.7$, or $L \approx 1.5 \times 10^6 L_\odot$. Errors in the distance, bolometric correction, and reddening probably make this luminosity estimate uncertain by a factor of 2–4.

Since MWC 349 is an extremely luminous, early-type star, it should have a radiation-pressure–driven wind (Castor, Abbott, and Klein 1975). One expects the general requirement of conservation of momentum (for single-scattering) to hold:

$$L > \dot{M} V_\infty c\,, \qquad (3)$$

where $V_\infty$ is the terminal velocity. An estimate of the mass-loss rate, which can be obtained by combining our velocity observations and Olnon's density distribution, therefore yields the minimum stellar luminosity which is consistent with the notion of a radiatively driven wind.

We obtain the terminal velocity from the [N II] emission, which occurs at distances $\sim 1.3 \times 10^{16}$ cm in our model. The FWHM of 6584 is 96 km s$^{-1}$, so we adopt $V_\infty = 50$ km s$^{-1}$. A disturbing feature, however, is that the [N II] profile is not the rectangular shape expected for a fully resolved, optically thin line formed in a shell expanding at constant velocity. We have been able to fit the line profile by convolving a rectangular profile of width 96 km s$^{-1}$ with a Gaussian profile of 40 km s$^{-1}$ half-width. From the evidence of the radio spectrum, we retain the constant velocity law, and interpret the Gaussian component as "turbulence." This turbulence may be a result of the radiation pressure instability discussed by MacGregor, Hartmann, and Raymond (1979), or it may reflect the historical variability of the source (Gottlieb and Liller 1978).

With $V_\infty \approx 50$ km s$^{-1}$, and using the density distribution of Olnon (1975), $\dot{M} \approx 3 \times 10^{-5} M_\odot$ yr$^{-1}$, so that $L > 10^{4.85} L_\odot$, which is an order of magnitude lower than our luminosity estimate. Therefore the observed mass loss is compatible with a radiatively driven wind. This conclusion is only weakly dependent on the adopted distance $D$, since $(\dot{M}/L) \approx D^{0.4}$ (cf. Olnon 1975). However, the wind is remarkably slow when compared with typical terminal velocities of $\sim$1000–3000 km s$^{-1}$ found for early-type stellar winds (Snow and Morton 1976). The hot stars most closely resembling MWC 349 are the B supergiants of the P Cygni class, which have relatively low-velocity winds. P Cygni itself has a mass-loss rate of $\sim 1.5$–$3 \times 10^{-5} M_\odot$ yr$^{-1}$ (Van Blerkom 1978; Barlow and Cohen 1977) and has $M_{\rm bol} \approx -10.4$ (Abbott 1978), very close to the parameters derived here for MWC 349, although the terminal velocity of 600 km s$^{-1}$ for P Cygni (Hutchings 1976, 1979) is an order of magnitude larger. Beals (1951) has discussed other "P Cygni" stars with H$\alpha$ profiles similar to the one shown in Figure 2 (profile type III), which may have absorption components blueshifted by as little as $\sim$100 km s$^{-1}$.

In order to see if such a low terminal velocity is consistent with a wind driven by radiation pressure, we apply the wind theory of Castor, Abbott, and Klein (1975, hereafter CAK). In this theory the momentum equation is written as

$$v\frac{dv}{dr} = \frac{-1}{\rho}\frac{dP}{dr} - \frac{GM}{r^2}\{1 - \Gamma_0[1 + M(t)]\} \qquad (4)$$

where $v$, $\rho$, and $P$ are the gas velocity, density, and pressure, respectively, and $\Gamma_0 = (\sigma_e L/4\pi c GM)$ is the ratio of radiation pressure force on electron scattering to gravity. The acceleration due to line absorption of photospheric radiation is approximated by the scaled force multiplier,

$$M(t) = kt^{-\alpha}\,,$$

where

$$t = \sigma_e V_T |dv/dr|^{-1}, \qquad V_T = (2kT/m_H)^{1/2}\,, \qquad (5)$$

and $k$ and $\alpha$ are constants adjusted to provide the best fit to calculations which explicitly include many lines.

We adopt the approximate values $\alpha = 0.7$ and $k = 1/30$ as suggested by CAK. For simplicity a critical point temperature of 35,000 K was used and a temperature law $T \propto r^{-1/2}$ was assumed to hold down to $1 \times 10^4$K, at which point the wind remains isothermal. The wind model is then parametrized by the adopted luminosity, mass, and critical radius; CAK show that the last quantity is approximately 1.74 times the photospheric radius. If we define a rough photospheric radius as that distance at which $\tau = 2/3$, then from equation (2) we find $R = 1.34 \times 10^{13}$ cm, and a critical radius $R_c \approx 2.3 \times 10^{13}$ cm. This estimate is uncertain, particularly since the density distribution will not be $r^{-2}$ close to the stellar surface, so we consider the range $1.4 \times 10^{13} \lesssim R_c \lesssim 3.5 \times 10^{13}$ cm.

With $L = 1.5 \times 10^6 L_\odot$, we require a mass estimate to complete the parametrization of the wind. We do this by choosing $\Gamma_0$, which, as we shall show below, controls the terminal velocity. The best results are for $\Gamma_0 \approx 0.9$, which implies a stellar mass in the vicinity of 40 $M_\odot$.

The results of CAK wind model computations are listed in Table 1. These calculations should be regarded as exploratory because of the large uncertainties in the choice of the initial stellar parameters and the crudity of the wind calculations. However, they clearly show that wind velocities an order of magnitude below typical terminal velocities may be achieved if $\Gamma_0 \approx 0.9$. This is the expected behavior from the approximate scaling law derived by Abbott (1978), $V_\infty{}^2 \propto M(1 - \Gamma_0)R^{-1}$. Model 2, with a velocity $\sim$2.2 times the observed velocity and $\sim$2.9 times the observed mass-loss rate, comes closest to the observations. At this level of matching, computational details not considered in these relatively unsophisticated models may become important. For example, Abbott (1977) has

TABLE 1

STELLAR WIND MODELS

| Model | $\Gamma_0$ | $r_c$ | $V(150)$ | $\dot{M}$ |
|---|---|---|---|---|
| 1 | 0.40 | 2.8 (+13) | 322 | 7.50 (−6) |
| 2 | 0.90 | 2.8 (+13) | 115 | 8.63 (−5) |
| 3 | 0.90 | 1.4 (+13) | 182 | 5.99 (−5) |
| 4 | 0.90 | 3.5 (+13) | 92 | 1.24 (−4) |
| 5 | 0.93 | 2.8 (+13) | 78 | 2.58 (−4) |
| Observed | | | 50 | 3 (−5) |

NOTE.—Numbers in parentheses are powers of 10 which multiply the preceding numbers. The critical radius $r_c$ is given in cm; $V(150)$, wind velocity at 150 $r_c$, is in km s$^{-1}$; and $\dot{M}$ is the mass-loss rate in $M_\odot$ yr$^{-1}$.

shown from detailed calculations that $k$ and $\alpha$ are not precisely constant, and that line overlap may be important, slowing wind acceleration. In addition, models 4 and 5 are more thermally driven than radiatively driven. The correct solution of the energy equations might well yield a result other than the very approximate radiative equilibrium relation $T \approx r^{-1/2}$, which could affect the wind structure of these models substantially. Despite the uncertainties, these calculations indicate that appropriately slow terminal velocities may be obtained in a radiatively driven wind from a star with a low surface gravity.

With the low effective gravity implied by $\Gamma_0 \approx 0.9$, the photosphere should be extended (Cassinelli and Hartmann 1975). The existence of an electron-scattering envelope with $\tau \approx 0.2$ demonstrated by the H$\alpha$ wings implies an extended photosphere. This is also suggested by the normal definition of the photospheric radius $R = (L/4\pi\sigma T_e^4)^{1/2} \approx 2.4 \times 10^{12}$ cm, using our adopted parameters. Our estimate of the luminosity is uncertain, and the appropriate choice of "effective" temperature in a spherical atmosphere is not well defined. Still, the fact that this radius is $\sim 5$ times smaller than the radius at which equation (2) predicts $\tau = 2/3$ also suggests that the photosphere is surrounded by an extended electron-scattering atmosphere as in Wolf-Rayet stars (Hartmann and Cassinelli 1977). (In such a spherical atmosphere the "photosphere" may occur at a thermalization depth where $\tau > 2/3$.)

Electron-scattering envelopes with $\tau \approx 1$ and $n \propto r^{-2}$ produce a flattening of the optical spectrum of the underlying hot star (Hartmann and Cassinelli 1977; Hartmann 1978). Thompson *et al.* (1977) suggested that the optical spectrum of MWC 349 is flatter than expected for a normal early-type star. However, uncertainties in the (very large) extinction corrections and in the continuum contamination by a neighboring star (Brugel and Wallerstein 1979) make this suggestion very difficult to prove.

## V. CONCLUSIONS

It appears that the low-velocity nature of the wind from MWC 349 may be reconciled with radiatively driven wind theory if the central star has a low effective surface gravity, possibly because it is overluminous for its mass. This model indicates that MWC 349 is not on the main sequence. The approximate radius derived from considerations of the wind optical depth is $\sim 2$ times that of P Cygni (Barlow and Cohen 1977), compatible with our interpretation of MWC 349 as a supergiant star of the P Cygni type. The alternative model of Thompson *et al.* (1977), in which the central star is on the main sequence, cannot account for the low-velocity nature of the wind. The high surface gravity of a main-sequence star should result in a fast wind typical of most early-type stars (Abbott 1978).

Past observations have suggested light variations (Gottlieb and Liller 1978), which may be the result of instabilities of a star near its Eddington luminosity. The photometric variations observed in MWC 349 have a range which is comparable to the historical variations of P Cygni, strengthening the basis of our interpretation of MWC 349 as an extreme P Cygni star.

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L. Hartmann, J. P. Huchra, and D. Jaffe: Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138