STRINGENT LIMITS ON THE IONIZED MASS LOSS FROM A AND F DWARFS

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ABSTRACT

Following the suggestion of Willson, Bowen, and Struck-Marcell that A- and F-type main-sequence stars might undergo significant mass loss due to pulsationally driven winds, we have obtained upper limits to the ionized mass loss from A and F dwarfs using VLA observations. These stringent upper limits show that the level of ionized mass loss would have at most only a small effect on stellar evolution. Radiative equilibrium atmospheric and wind models for early A dwarfs indicate that it is highly likely that a wind flowing from such stars would be significantly ionized. In addition, late A and early F dwarfs exhibit chromospheric emission indicative of significant nonradiative heating. Our mass-loss limits are thus representative of the total mass-loss rates for these stars. Therefore, we conclude that A and F dwarfs are not losing sufficient mass to cause A dwarfs to evolve into G dwarfs as has been proposed.

Subject headings: stars: evolution — stars: mass loss — stars: pulsation — stars: radio radiation

I. INTRODUCTION

Willson, Bowen, and Struck-Marcell (1987) suggested that main-sequence A and F stars that lie in the δ Scuti pulsational instability strip might lose mass at rates between $10^{-5}$ and $10^{-8} M_\odot \text{yr}^{-1}$. Such large mass loss rates over a significant portion of the main-sequence lifetime of these stars would have severe implications for stellar evolution. The net effect would be for A and F dwarfs to evolve down the main sequence to become mid-F or G dwarfs. This would result in an underabundance of A and early F dwarfs and an excess population of lower mass stars compared to the initial mass function of the stellar population.

The properties of δ Scuti stars, which lie in the extension of the Cepheid instability zone down to the main sequence, have been reviewed by Breger (1979) and Wolff (1983). The instability strip covers the effective temperature range of 8800-7500 K at the zero-age main sequence. The δ Scuti variables show radial and nonradial pulsations with periods less than 0.3 days and often have multiple periods present. The photospheric radial velocity amplitude is generally less than 10 km s$^{-1}$. Only about a third of the A and F dwarfs and subgiants lying in the δ Scuti instability strip show detectable pulsations, at a detection limit corresponding approximately to photometric variability of less than 0.01 magnitudes at V.

The expected properties of the proposed winds are not discussed in great detail by Willson et al. Their proposed mechanism for mass loss is the deposition of pulsational energy into a stellar outer atmosphere whose effective surface gravity is somewhat reduced by rapid rotation. It is not clear if rapid rotation is a necessary condition for this mass-loss scenario. The projected rotational velocities of A dwarfs range up to ~250 km s$^{-1}$, which is considerably less than the photospheric escape velocity of 600 km s$^{-1}$. Therefore the wind-driving mechanism must still impart considerable energy and momentum to the wind as it lifts material out of the stellar gravitational potential well. Willson et al. suggested that the Herbig Ae stars, which definitely show substantial mass loss, might be stars undergoing this mass-loss process, but these stars are pre-main sequence objects (Strom et al. 1972; Finkenzeller 1985), and cannot be examples of main-sequence A dwarf mass loss.

Willson et al. used a simple exponential decay law to describe the temporal behavior of the mass loss. By choosing appropriate ad hoc initial mass-loss rates and time scales they can convert 2 $M_\odot$ stars into G dwarfs even though the mass-loss driving mechanism does not operate for a significant portion of the mass-losing evolution. The red edge of the δ Scuti instability strip lies among the earliest F stars and we believe it very unlikely that mass loss driven by the δ Scuti pulsations would continue once the star leaves the instability strip.

The ionization state of the wind is of crucial importance in determining which observational techniques would be appropriate for the detection of such winds. For predominantly neutral winds the appropriate techniques would include observation of circumstellar absorption lines, circumstellar molecular emission lines, and 21 cm H i line emission. If the winds are ionized, observation of free-free microwave continuum emission should offer the best hope for detection. However, if the winds are at coronal temperatures (i.e., greater than 10$^6$ K), then X-ray flux measurements may well provide even stronger constraints on the mass-loss rate (Drake 1988).

If A and F dwarfs actually evolve into G dwarfs due to mass loss, then this process would have serious implications for the study of stellar evolution, light element abundances in solar like stars and the early history of the solar system. In this paper we describe our observational test of this mass loss by searching for radio continuum emission from A and F dwarfs that
would be emitted by a fully or partially ionized wind from these stars. In § II we describe our radio continuum observations, while in § III we consider the likely physical properties of winds from A and F dwarfs and derive limits on ionized mass-loss rates.

II. VLA Radio Continuum Observations of A and F Stars

A sample of 10 A and F stars listed in Table 1 was observed with the NRAO Very Large Array (VLA) on 1988 May 27. In addition, we have used the results obtained by Bookbinder and Walter (1987) for seven additional F dwarfs to extend our analysis. The stars were selected using the following criteria to ensure the greatest likelihood for detection of radio emission: (1) all are close with known distances, ranging from 3.4 to 28 pc, (2) most show large projected rotational velocity \( v \sin i \), (3) most are known or suspected pulsating stars, and (4) a number are members of the relatively young Ursa Major cluster with ages of \( \sim 3 \times 10^8 \) yr. By selecting stars showing pulsations and high-rotational velocities, we are meeting the fundamental conditions of the proposed mass-loss mechanism. By observing relatively young stars we are studying stars at an evolutionary stage where the mass loss has not died away, if the exponential decay law proposed by Willson and colleagues is indeed valid.

In Table 1 the entries in the column headed "pulsator" indicate the degree of pulsational activity shown by the star; "\( \delta \) Scutum" indicates a star with a single well-defined pulsational period, "\( \delta \) Scut?" indicates stars with multiple periods or weak pulsations, and "\( \delta \) Scut??" indicates stars suspected to show low-level radial velocity variations that are probably pulsational in origin.

Our observations were made in the C/D array configuration at 6 cm using two adjacent 50 MHz bandwidths centered at 4835 and 4885 MHz. The observations were calibrated using standard software on the VLA DEC 10 computer. Local phase calibrators were observed at least every 30 minutes and bracketed the observations of the A and F stars. 3C 48 was used as the primary flux calibrator; its 6 cm flux was taken to be 5.59 Jy. Subsequent reduction was performed using the AIPS reduction package. The data from the two adjacent frequencies were combined, and aperture synthesis mapping performed using the MX and ASCAL routines. The maps were calculated using natural weighting.

None of the sources were detected at the 3 \( \sigma \) levels given in Table 1. The on-source observing time for the stars ranged from 30 minutes to 1 hour. The derived 3 \( \sigma \) levels were in all cases consistent with the number of visibility records used to produce the maps of the source fields. The upper limits were measured from areas close to the expected positions of the stars, which were taken from the SAO Catalog and corrected for proper motion to the date of observation.

III. Discussion

a) Estimation of Ionized Mass-Loss Rates

In addition to the radio emission from an ionized wind, we must consider the possible contribution of 6 cm radio emission from the tail of the stellar photospheric blackbody energy distribution. The strength of this emission is given by

\[
S_v = 1.42 \times 10^{-4} \left( \frac{T_b}{10^4} \right) \phi^2 \text{ mJy},
\]

where \( \phi \) is the photospheric angular diameter in milliarcseconds, and \( T_b \) is the blackbody temperature (see Drake and Linsky 1986). The angular diameters of nearby A and F dwarfs are typically only a few milliarcseconds and the effective temperatures range from 9000 to 6000 K for the stars in our sample. The expected photospheric radio emission is, therefore, clearly orders of magnitude smaller than the observed upper

| Table 1: A and F Stars Observed with the VLA |
|-----------------|-------|---------|---------|-----------------|-----------------|
| Star            | HD    | Spectral Type | \( d \) (pc) | \( v \sin i \) (km s\(^{-1}\)) | Pulsator | \( S_v \) (mJy) | \( \log M^\ast \) (\( M_\odot \) yr\(^{-1}\)) |
| \( \xi \) PsA    | 216956| A3 Va       | 6.7       | 100              | ...      | \( \leq 0.10 \) | -9.81          |
| \( \beta \) Leo  | 102647| A3 V        | 12        | 121 \( \delta \) Scut? | \( \leq 0.11 \) | -9.38          |
| \( \delta \) Leo | 97603 | A4 IV       | 21        | 181 \( \delta \) Scut? | \( \leq 0.11 \) | -9.04          |
| \( \xi \) Oph    | 159561| A5 V        | 15        | 219 \( \delta \) Scut? | \( \leq 0.10 \) | -9.26          |
| 18 UMa          | 79439 | A5 V        | 24        | 157 \( \delta \) Scut? | \( \leq 0.15 \) | -8.83          |
| \( \varepsilon \) Aql | 187642| A7 IV-V     | 5.0       | 242              | ...      | \( \leq 0.10 \) | -10.01         |
| \( \varepsilon \) Cep | 203280| A7 V        | 15        | 246 \( \delta \) Scut? | \( \leq 0.12 \) | -9.22          |
| \( \varepsilon \) Cep | 211336| A9 IV       | 24        | 86 \( \delta \) Scut? | \( \leq 0.13 \) | -9.02          |
| \( \eta \) UMa   | 84999 | FO IV       | 24        | 110 \( \delta \) Scut? | \( \leq 0.14 \) | -8.85          |
| 37 UMa          | 91480 | F1 V        | 28        | 87               | ...      | \( \leq 0.11 \# \) | -8.83          |
| 10 Vir/AB       | 110379| F1V + F0 – 2V | 10.1     | 28/30 \( \delta \) Scut?? | \( \leq 0.12 \# \) | -9.47          |
| \( \eta \) Psc   | 8723  | F2 V        | 26        | 61               | ...      | \( \leq 0.075 \# \) | -9.00          |
| \( \beta \) Cas  | 432   | F2 III      | 14        | 70 \( \delta \) Scut? | \( \leq 0.12 \) | -9.26          |
| \( \lambda \) Leo | 99028 | F4 IV       | 19        | 20 \( \delta \) Scut? | \( \leq 0.12 \# \) | -9.06          |
| \( \xi \) CMi    | 111456| F5 V        | 24        | 36               | ...      | \( \leq 0.075 \# \) | -9.04          |
| \( \theta \) Boo | 61421 | F5 IV-V     | 3.4       | 6 \( \delta \) Scut? | \( \leq 0.13 \# \) | -10.15         |

* Derived from the parallaxes in Hoffleit 1982.
* From Hoffleit 1982, see § II for clarification of these symbols.
* The 3 \( \sigma \) upper limits determined directly from each map.
* Upper limits assuming \( v = 400 \) km s\(^{-1}\).
* UMa Stream star.
* From Bookbinder and Walter 1987.
limits. Thus this emission will not contaminate any wind signature.

The observed radio upper limits can be converted into limits on the ionized mass loss following the derivation of Drake and Linsky (1986), which is based on the formula for spherically symmetric stellar winds by Wright and Barlow (1975) and Panagia and Felli (1975). For observations at 6 cm, the ionized mass-loss rate ($M$) and velocity ($V$) of an optically thick stellar wind are related to the flux density ($S$) of free-free radio emission from the wind by

$$\left( \frac{M}{V} \right)^{4/3} = \frac{S}{1.6 \times 10^{17} D^2 T_4^{-0.1}},$$

where $D$ is the stellar distance in parsecs, $T_4$ is the wind temperature in units of $10^4$ K, and $M$, $V$, and $S$ are in units of $M_\odot$ yr$^{-1}$, km s$^{-1}$, and mJy, respectively. The optically thick wind formula is used here, because the flux density upper limits are at a level that implies that the winds have effective radio angular diameters of many stellar radii (see eq. [4] of Drake and Linsky 1986).

The ionized mass-loss rates implied by the 3 $\sigma$ upper limits are given in Table 1 and were calculated assuming that the wind has a velocity of 400 km s$^{-1}$ and a temperature of 6000 K (see § 11b). The weak dependence of the mass-loss rate on temperature ensures that the adopted temperature only marginally affects the results. The actual wind velocity is unknown and would depend on the relative amounts of energy and momentum deposited above and below the wind critical point (see e.g., Holzer and MacGregor 1985). Since the mass-loss rate and wind velocity are coupled linearly in equation (2), the mass-loss rate will only be larger if the wind velocity is larger. It seems unlikely that the wind velocity would be larger than the escape velocity ($\approx 600$ km s$^{-1}$), as the only stellar winds with velocities greatly exceeding the surface escape velocity are hot, radiatively driven winds. Moreover, if the velocity were considerably lower than 400 km s$^{-1}$, then the mass-loss rate upper limits would become even more stringent.

In Figure 1 we show the mass loss rate upper limits plotted against $B-V$ color, which is a proxy for effective temperature and mass along the main sequence for the stars being studied (see e.g., Wolff 1983). The relationships between $B-V$ and effective temperature and mass are in general observationally based and should be representative of A dwarfs whether they are losing mass or not, provided that all A dwarfs undergo the same evolution. Also shown are four mass-loss loci discussed by Willson, Bowen, and Struck-Marcell (1987) and Guzik, Willson, and Brunish (1987). Our upper limits on the ionized mass-loss rates are clearly at least an order of magnitude lower than these curves. Our data indicate that early A dwarfs at age $3 \times 10^6$ yr (e.g., δ Leo and α Oph) have ionized mass-loss rates no larger than $4.5 \times 10^{-10} M_\odot$ yr$^{-1}$, and that by ages of a few $10^9$ yr (α PsA, α Aql) the ionized mass-loss rate for A dwarfs is less than $10^{-10} M_\odot$ yr$^{-1}$. The ages of these stars were determined from evolutionary tracks of Maeder and Meynet (1988), which assume no mass loss for A dwarfs.

**b) Likely Ionization State of A and F Dwarf Winds**

The ionization state of a stellar wind strongly affects the accuracy and interpretation of an ionized mass loss upper limit. Therefore we have carefully examined the likely physical properties of the outer atmospheric layers of A and F dwarfs. First, we note that late A and F dwarfs show chromospheric and transition region emission lines (see Jordan and Linsky 1987). The strong ultraviolet photospheric continuum shown by A stars of earlier spectral type makes it very difficult to determine whether they also possess chromospheres. The earliest example of this phenomenon is α Aql (A7 IV-V), one of the stars in our sample, which shows strong H Lyz emission (Blanco, Catalano, and Marilli 1980) and X-ray emission (Schmitt et al. 1985). Most F dwarfs also show coronal X-ray emission. Therefore it is very likely that any wind flowing from a dwarf of spectral type A7 or later would contain hydrogen that is at least partially ionized.

In order to examine the likely properties of winds from early A dwarfs we have calculated atmospheric models appropriate for an A2-3 dwarf. Our procedure was to calculate first a LTE radiative equilibrium model with no wind and check for non–LTE effects using this initial model as a starting configuration, and secondly construct a wind model with an enhanced particle density. In our analysis we have assumed that the individual shocks in the wind are quickly subsumed into a smoothly varying, average wind. Due to the absence of specific predictions concerning the wind by those advocating this mass loss mechanism, we have considered a wide range of values for parameters, such as mass-loss rate and wind velocity, that allow a relevant examination of the feasible wind properties.

Initially a plane-parallel LTE model in radiative and hydrostatic equilibrium with an effective temperature of 9000 K and a surface gravity of $10^4$ cm s$^{-2}$, corresponding to an A2-3 dwarf, was calculated using the program described by Hubeny (1981, 1988). It is not possible to calculate models for lower effective temperatures with this program due to the onset of partial convection. The electron temperatures in the LTE model are shown in Figure 2(a), while the electron and total number densities are shown in Figure 2(b). The electron temperature rises from 6600 K at a mass column density of

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**Fig. 1.—** The ionized mass-loss rate upper limits derived from VLA 6 cm observations plotted against stellar $B-V$ color. These limits were derived using a wind velocity of 400 km s$^{-1}$. Note that most of the scatter merely reflects the differing distances that these stars lie from the Sun. The δ Scuti instability strip covers the range $0.09 < B - V < 0.26$ based on Breger (1979) and models of Relyea and Kurucz (1978). The mass scale used to place the evolutionary models of Willson et al. (1987) and of Guzik et al. (1988) onto this figure is shown at the top of the figure. The original mass-loss formula of Willson et al. is labeled (a). Models 1, 2 and 3 of Guzik et al. are labeled (b), (c), and (d), respectively.

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2 \times 10^{-6} \text{ g cm}^{-2} \text{ to } 7300 \text{ K at } 10^{-1} \text{ g cm}^{-2}. For mass column densities smaller than \(10^{-4} \text{ g cm}^{-2}\) hydrogen is essentially fully ionized. Non-LTE effects on the model were found to be small, when the LTE model was used as an input model to the radiative transfer code MULTI (Carlsson 1986). Only a slight reduction (30\%) in the level of ionization occurred at the top of the model. The ionization fractions in these models are determined entirely by the absorption of photospheric radiation in the Balmer continuum and recombination in the higher continua. Both H Lyα and the Lyman continuum are essentially in detailed balance. The radiation in the Balmer continuum is formed in the photospheric layers, and the photoionizing radiation in higher layers can be characterized by a radiation temperature of \(\sim 8000 \text{ K}\).

The primary difference between the structure of the hydrostatic and wind models is that the total particle densities are enhanced in the wind model, decreasing as the inverse square of the distance from the star, \(r\), rather than exponentially. If the predominant contribution to the electron density in the wind is from partially ionized hydrogen, then the emergent radio spectrum is determined entirely by the equation of continuity and the fractional ionization of hydrogen as a function of radius.

We estimate the degree of ionization using the formula of Hartmann and MacGregor (1980) for the hydrogen ground-state departure coefficient, \(b_1\), which assumes detailed balance in the Lyman lines and continuum. We used a radiation equilibrium temperature of 6500 \text{ K} and a radiation temperature of 8000 \text{ K} in these calculations. There are two essential differences between the hydrostatic and wind models which would tend to lower the fractional ionization of hydrogen:

1. The photoionizing radiation is more dilute at larger radii from the star (by a factor \([R_*/r]^{-2}\) compared with the plane parallel case, where \(R_*\) is the stellar radius), and
2. In a moving atmosphere the assumption of detailed balance in Lyα may be inappropriate (Schmutz and Hamann 1986), since enhanced photon escape via Doppler shifted lines can greatly reduce the \(n = 2\) level population relative to the ground state of hydrogen, thereby reducing the ionization fraction.

However, the second effect is probably unimportant for our models, because any velocity gradients present near the radio photosphere are much smaller than those considered by Schmutz and Hamann (1986), and partial redistribution effects will enhance the trapping of photons in H Lyα thereby favoring detailed balance in the line.

Using the equations of continuity and charge conservation (with \(N_e = N_p\)), we have computed the fractional ionization in representative wind models with mass loss rates of \(1 \times 10^{-9}\) and \(5 \times 10^{-9} \text{ M}_\odot \text{ yr}^{-1}\) and velocities of 40 and 400 \text{ km s}^{-1}, assuming a constant velocity law far from the star. Asymptotically, the computed ionization fractions tend to constant values beyond \(2 R_*\), because both the photoionizing mean intensity and the total particle density drop as \(r^{-2}\), while all other parameters (e.g., gas temperature, photoionizing field radiation temperature) remain fixed. Table 2 shows values for the asymptotic ionization fractions. For this range of wind parameters, the wind from an A dwarf must have a hydrogen fractional ionization of at least 0.37. It is likely that these are lower limits to the actual ionization fractions because (1) when the Lyman continuum becomes optically thin, recombination can no longer balance photoionization in the Lyman continuum, and (2) we have assumed that there is no additional heating of the wind other than by the radiation field. However, it is extremely unlikely that the pulsational driving of the wind will be by purely adiabatic shocks (in no other stellar case are purely adiabatic shocks found to be appropriate) and therefore the driving of the wind will also result in heating of the wind. Given that the wind must already be partially ionized, the

### Table 2

<table>
<thead>
<tr>
<th>Wind Velocity (km s(^{-1}))</th>
<th>Mass-Loss Rate (10(^{-9}) M(_\odot) yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>(f_{\text{ion}})</td>
</tr>
<tr>
<td>6.6</td>
<td>(S_{6\text{ cm}}) 0.63</td>
</tr>
<tr>
<td>400</td>
<td>(f_{\text{ion}})</td>
</tr>
<tr>
<td>0.92</td>
<td>(S_{6\text{ cm}}) 0.51</td>
</tr>
</tbody>
</table>

\(f_{\text{ion}}\) is the ratio of the proton number density to the total number density.

Assuming a distance of 10 pc.; in mJy.
result of the shock heating must be to produce a wind that is very nearly fully ionized.

From equation 2, we can estimate the flux densities predicted from the model winds and compare these with the observed 6 cm upper limits. The predicted flux densities are listed in the Table 2, assuming a distance of 10 parsecs. The upper limits from the VLA observations are considerably smaller than the flux densities predicted by wind models with mass-loss rates similar to those advocated by Willson et al., even when the effects of partial ionization are taken into account.

IV. CONCLUSIONS

We have searched for radio continuum emission from A and F dwarfs using the VLA. None of the 17 stars observed was detected even though we adopted selection criteria that maximized the likelihood of detecting this emission if it exists. Our observational investigation provides flux density upper limits that are close to the best achievable with currently available astronomical facilities. The observations have been used to derive stringent upper limits on the ionized mass-loss rates from A and F dwarfs. In addition, we have shown that it is extremely likely that the wind from these stars would be at least partially ionized and that our observed limits are therefore indicative of the total mass-loss rates from these stars.

Even if the mass-loss rates are only $10^{-10} M_\odot$ yr$^{-1}$, the cumulative mass loss would be small but not entirely negligible when integrated over the main-sequence lifetimes of A and early F dwarfs, which for 2 $M_\odot$ and 1.5 $M_\odot$ stars is $1.7 \times 10^9$ and $5.4 \times 10^9$ yr, respectively (Maeder and Meynet 1988).

With our current data we are not able to discount mass loss at this level. However, we do conclude that these stars are not losing mass at the rates suggested by Willson et al. and that it is extremely unlikely that A dwarfs are converted into G dwarfs by mass loss.

It is difficult to extend the search for radio continuum emission to sensitivity levels that will provide mass loss rate upper limits much more stringent than those provided by our current observations. However, we intend to obtain VLA data at 3.6 cm for the stars that are most crucial in defining the mass loss upper limits. Limits that are approximately a factor of 0.67 smaller should result due to the increased sensitivity at 3.6 cm and the expected increase of a thermal spectrum toward shorter wavelength.

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