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DETECTION OF RADIO CONTINUUM EMISSION FROM PROCYON

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ABSTRACT

We have detected the F5 IV–V star Procyon as a weak and variable 3.6 cm radio continuum source using the Very Large Array.[2] The inferred radio luminosity is $11.7 \leq \log L_\nu \leq 12.2$ which is similar to, though somewhat higher than, the X-band luminosity of the active and flaring Sun. The 33 μJy flux density level at which we detected Procyon on four of five occasions is close to the 36 μJy radio flux density expected from a model in which the radio emission consists of two components: optically thick "stellar disk" emission with a 3.6 cm brightness temperature of 2×10^4 K that is 50% larger than the solar value, and optically thin coronal emission with an emission measure the same as that indicated by *Einstein* and *EXOSAT* X-ray flux measurements in 1981 and 1983. The maximum mass-loss rate of a warm ($T_e \sim 10^4$–10^5 K) stellar wind is constrained by our radio observations to be less than $2 \times 10^{-11}\ M_\odot\ \mathrm{yr}^{-1}$. An elevated flux density of 115 μJy observed on a single occasion may have been associated with a radio outburst or flare, or, alternatively, been caused by the rotation onto the visible hemisphere of a large, intense active region. In either case, this observation provides circumstantial evidence for the existence of highly localized magnetic fields on the surface of Procyon.

Subject headings: radiation mechanisms: miscellaneous — radio continuum: stars — stars: individual (α Canis Minoris)

1. INTRODUCTION

The only solar-type dwarf star from which microwave emission has until now been unambiguously detected is the Sun. In terms of specific luminosity L_ν (ergs $\mathrm{s^{-1}\ Hz^{-1}}$), the X-band (3.6 cm) brightness of the quiet sun corresponds to $\log L_\nu = 10.8$; the active Sun reaches $\log L_\nu = 11.15$, while, during the largest type IV burst, the Sun can reach $\log L_\nu = 12.4$ (Kruger 1979). Using the standard relation between L_ν and flux density S_ν,

$$L_\nu = 1.20 \times 10^{12} S_\nu D^2 ,$$

where S_ν is in mJy and D is in pc, the corresponding flux densities of the Sun, if viewed from a distance of 1 pc, are 0.05, 0.12, and 2.1 mJy for quiet, active, and flaring states, respectively. These weak flux density levels demonstrate the difficulty of detecting solar-type radio emission from ordinary stars at even the closest of distances.

The first sensitive (≤ 1 mJy) searches for microwave emission from solar-type stars were those of Bowers & Kundu (1981), Gary & Linsky (1981), and Linsky & Gary (1983). In all but one case no emission was detected. The typical upper limits of $\log L_\nu < 13.0$ established in these studies were generally well above the brightest levels at which the Sun has ever been observed. The solitary exception was χ^1 Ori (G0 V+M V), which Linsky & Gary (1983) observed as a 1.1 mJy source on 1980 October 2. However, this source has never been convincingly redetected since that occasion in an array of high enough spatial resolution to identify which member of this close (angular separation 0".65) visual binary system is the radio source. More recent VLA studies (Bookbinder & Walter 1987; Pallavicini, Willson, & Lang 1985; Drake et al. 1992) have also failed to detect any F or G stars, with the most sensitive upper limits being established for the nearby F5 IV–V star Procyon (α CMi) for which Bookbinder & Walter (1987) found $\log L_\nu < 12.3$ at 6 cm, and for the G8 V star τ Cet for which Drake et al. (1992) found $\log L_\nu < 12.4$ at 3.6 cm.

Because of the addition to the VLA's telescopes a few years ago of sensitive X-band receivers, however, it is now possible in a 10 hr integration to reach a 3 σ detection limit of 18 μJy, which is a factor of ≥ 6 fainter than the limit of any of these previous searches. In view of this enhancement to the performance of the VLA, we have undertaken a search for radio continuum emission from Procyon ($D = 3.5$ pc), which is one of the nearest, and potentially brightest at radio wavelengths, of the solar-type stars that are accessible to this telescope. The properties of this star are summarized in Table 1. Because Procyon is earlier in spectral type and more evolved than the Sun, its radius is double the solar value. Under the assumption that Procyon's X-band brightness temperature T_b^X is identical to the (quiet) solar value of 1.3×10^4 K, one would then expect a stellar X-band flux density of 16 μJy; on the other hand, if Procyon's T_b^X is similar to the (disk-averaged) active solar value of 3.0×10^4 K, then one might expect a flux density of 36 μJy. Additional sources of radio emission (discussed in more detail in § 3) include optically thin emission from the 10^6 K corona, from a proposed 10^4–10^5 K stellar wind, or from

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TABLE 1

BASIC PARAMETERS OF PROCYON

Parameter	Value
Spectral type	F5 IV–V+DA (or DF)
Visual binary separation	$5\farcs2$
Distance D	3.5 parsecs
Angular diameter ϕ_*	5.5 mas
Mass M_*	1.77 $M_\odot$
Radius R_*	2.1 $R_\odot$
Escape velocity $v_{\rm esc}$	570 km s^{-1}
Rotational velocity $v_{\rm rot}$ sin i	2.8 km s^{-1}
Effective temperature $T_{\rm eff}$	6560 K

transient events similar to solar flares or bursts. Even if the latter contributions are negligibly small, the 16–36 μJy of radio emission expected from Procyon's chromosphere should be (just) detectable in a long VLA observation at X-band.

2. OBSERVATIONS

Observations of Procyon were carried out in five separate observing runs in 1991 April and May when the VLA was in its D-configuration. All observations were at X-band and used the full 100 MHz frequency bandwidth. This combination of array and observing wavelength gives a synthesized half-power beam width of $\sim 5''$. The phase center of the observation was displaced $11\farcs5$ to the north of the position of Procyon in order to avoid the possibility of any associated radio source being confused with a phase-center artifact. In the first run about 1.2 hr of source data were obtained, while in each of the last four runs about 2.4 hr of on-source data were obtained, for a total of 10.8 hr. The data were reduced using the AIPS software package on NRAO's Charlottesville Convex computer. Each data set was reduced independently, and maps of the source field were made for each run. The (u, v) data from the last four runs were also combined in order to produce a map of the source field using this concatenated data set (see Fig. 1). The complete results are listed in Table 2, where all quoted flux densities are peak values in μJy per beam obtained from the AIPS task IMEAN (the more sophisticated source fitting routines like IMFIT have problems in modeling weak ($\leq 4\ \sigma$) sources). For comparison, we also list in this table the flux density obtained in the same way for a serendipitous, presumably extragalactic source (hereafter referred to as S1) at $\alpha = 7^{\rm h}36^{\rm m}44\fs0$, $\delta = 5°24'19''$ (equator and equinox of 1950.0) that lies several arcminutes away from the position of Procyon. It can be seen that the rms noise in the map made from an individual run was typically about 16 μJy, except for the first shorter run for which it was 28 μJy. The rms noise for the concatenated data set was 8 μJy, i.e., a factor of 2 better than that of a typical individual data set.

TABLE 2

PROCYON X-BAND OBSERVATIONS IN 1991

Run	Date	Procyon Flux (rms) (microjanskies)	Flux of source S1 (microjanskies)
1	Apr 13	115 (28)	240
2	Apr 29	29 (17)	208
3	May 13	30 (15)	236
4	May 18	56 (16)	293
5	May 27	34 (15)	257
2+3+4+5	4-run sum	33 (8)	248

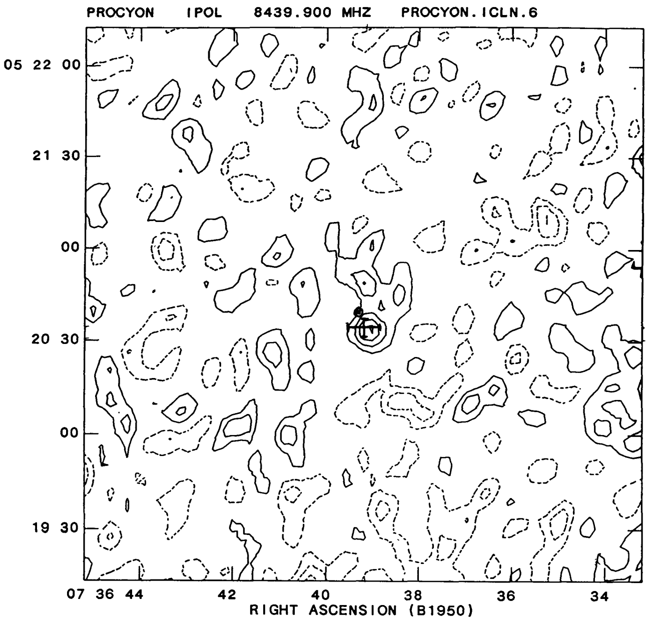

FIG. 1.—The cleaned map of the Procyon field constructed using the concatenated (u, v) data from the last four observing runs. The contour levels are $(-3, -2, -1, 1, 2, 3, 4)$ times the rms level of 8 μJy. The predicted positions of Procyon A and B are indicated by a cross and a ⊙ symbol, respectively. The arms of the cross marking Procyon A represent $\pm 2\ \sigma$ error bars in its optical position. Notice that the radio peak coincides with Procyon A to within these uncertainties, but not with Procyon B.

According to the SAO catalog, the optical position of Procyon A at epoch 1991.28 was $\alpha = 7^{\rm h}36^{\rm m}39\fs16$, $\delta = 5°20'34\farcs3$ (equator and equinox of 1950.0). A weak radio source was definitely detected in two of the observing runs with significance levels of 4.1 σ on April 13 and of 3.5 σ on May 18, and possibly detected with significance levels of 1.7–2.3 σ in the other three runs, at a position of $\alpha = 7^{\rm h}36^{\rm m}39\fs00 \pm 0\fs19$, $\delta = 5°20'34\farcs5 \pm 1\farcs4$, where the large error bars of the radio position reflect the large HPBW of $5\farcs1$ and the low level of statistical significance of the radio source. The error box of the radio source includes the optical position of Procyon A, but not that of its visual white dwarf companion Procyon B, which is predicted to lie $5\farcs2$ away from Procyon A at a position angle of 26° in a roughly north-northeast direction. The map constructed from the concatenated data shows, in addition to the 4.1 σ source we identify as Procyon, a 3 σ peak of 25 μJy (hereafter referred to as S2) lying about 14″ almost due north of Procyon, as well as some very weak (at the 1–2 σ level) extended structure enclosing both peaks. Neither the weak point source S2 nor the extended structure is convincingly visible in maps made from the individual runs. In fact, the source S2 is close to the phase reference position and may indeed be a phase center artifact. It is interesting, although perhaps coincidental, that the position angle of S2 relative to Procyon is almost precisely the same as that of Procyon B (the white dwarf visual companion), although the separation is $14\farcs3$ for the second radio source compared to $5\farcs2$ for Procyon B. Hereafter, we will restrict our discussion to the point source we have associated with Procyon A.

3. RADIO EMISSION MECHANISMS

It can be seen from Table 2 that Procyon was clearly (i.e., at $\geq 3\ \sigma$ significance) detected both on 1991 April 13 (at a level of

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115 ± 28 μJy) and on 1991 May 18 (at 56 ± 16 μJy). On the other three occasions a weak 2 σ source of ~ 30 μJy did appear to be present at the position of Procyon. The high value found for Procyon's flux density on April 13 is almost certainly real and not due to a calibration error, since the flux density measured for the serendipitous source S1 on that date is 240 μJy, which is very close to the average value of 247 μJy found for this source over the five observing runs. In the concatenated data set including all of the observations except for the April 13 run, the source at the position of Procyon is also significantly detected at a level of 33 ± 8 μJy (see Fig. 1). Thus, our VLA observations of Procyon are consistent with the star usually being a 33 μJy source at 3.6 cm (equivalent to a specific luminosity of $\log L_\nu = 11.69$), except that on occasion it may appear significantly brighter, in one case at a level of 115 ± 28 μJy (or $\log L_\nu = 12.23$). What might the possible sources of 3.6 cm emission be in a star like Procyon and at what flux density levels might they be expected to contribute? For lack of any other star with detailed radio observations, we will use the solar case as a guide, although, it should be pointed out, the form in which stellar activity manifests itself on Procyon may be qualitatively as well as quantitatively different than the solar case, due to Procyon having a much thinner convective envelope than the Sun has.

The potential sources of the radio emission detected from Procyon are: (i) the finite stellar disk of the star (the free-free opacity is expected to result in optical depth unity at 3.6 cm occurring at some level in the chromosphere); (ii) compact regions of activity which have higher opacity at radio wavelengths due to their higher density (free-free opacity) and/or magnetic field (gyroresonance absorption) and hence have higher brightness temperature at cm wavelengths than the rest of the stellar surface; (iii) the 10^6 K X-ray emitting corona detected by *Einstein* and *EXOSAT*; (iv) a partially or completely ionized 10^{4-5} K stellar wind; and (v) transient sources of radio emission that may be analogous to solar flares or bursts, and producing gyrosynchrotron emission from either high-temperature (10^{7-10} K) or power-law electrons in the presence of strong localized magnetic fields.

3.1. *Stellar Disk Emission*

Using the standard formula for the radio flux from a blackbody with brightness temperature T_b and an angular diameter $\phi_* = 5.5$ mas, the predicted 3.6 cm flux density is

$$S_\nu(\text{disk}) = 12.2\ \mu\text{Jy}(T_b/10^4\ \text{K})\ .$$

If T_b is assumed to be the effective temperature, $T_{\text{eff}} = 6560$ K, then $S_\nu(3.6\ \text{cm}) = 8$ μJy. However, in the presence of a significant chromospheric temperature rise as is known to occur in Procyon, then $T_b > T_{\text{eff}}$, since $\tau_\nu(3.6\ \text{cm}) \sim 1$ will be reached at a height in the stellar atmosphere where the electron temperature $T_e \geq T_{\text{eff}}$. We have used a model chromosphere/corona of Procyon to estimate $T_b^X \sim 2\text{–}3 \times 10^4$ K, implying a predicted 3.6 cm flux density of 24–37 μJy that is consistent with the observed flux density being mostly or completely due to stellar disk emission.

3.2. *Emission from Active Regions*

If the surface of Procyon is not homogeneous but is covered by an areal fraction f of active regions for which $T_b = T_{\text{act}} \gg T_*$, where T_* is the brightness temperature of the quiescent stellar disk, then the predicted 3.6 cm flux density is

$$S_\nu(\text{AR}) = 12.2\ \mu\text{Jy}[fT_{\text{act}} + (1-f)T_*]/10^4\ .$$

We have to estimate what T_{act} might be for a plagelike area on Procyon. For the Sun, the presently available data for active regions (e.g., White, Kundu, & Gopalswamy 1992; White 1992) indicate that the brightness temperature at 3.6 cm can range from $\leq 10^5$ K up to coronal values of $\sim 1.7 \times 10^6$ K, depending on the local magnetic field strength, which determines the gyroresonance absorption. If we assume $T_* = 1 \times 10^4$ K and $T_{\text{act}} = T_{\text{cor}} = 1.5 \times 10^6$ K (Jordan et al. 1986) for Procyon, then the observed value of S_ν allows us to deduce the active region covering factor. For $S_\nu = 33$ μJy, we infer $f = 1.1\%$, while for $S_\nu = 115$ μJy, $f = 5.7\%$. On the other hand, if $T_{\text{act}} = 10^5$ K, then we deduce much larger covering factors of 18.9% ($S_\nu = 33$ μJy) and 93.6% ($S_\nu = 115$ μJy). The implicit assumption here is that Procyon has localized areas of strong magnetic field similar to those characterizing solar active regions. However, previous UV variability studies (e.g., Ayres 1991) suggest that F stars in general and Procyon in particular exhibit no detectable modulation in transition-region lines like C IV, which are known to be enhanced in solar active regions. This appears to be in conflict with the large variation in the covering factor (a factor of ~ 5) deduced in this particular model of Procyon's radio emission. We thus consider it unlikely that the high radio flux on April 13th relative to the other observing runs was due to a factor of 5 decrease in the active region covering factor between April 13 and April 29.

3.3. *Coronal Thermal Emission*

The optically thin radio emission expected from the corona of Procyon, assuming the X-ray emission measure of 4×10^{50} cm^{-3} and the previously cited coronal temperature of 1.5×10^6 K (Jordan et al. 1986), is $S_\nu(\text{cor}) = 12$ μJy. Here we have used the standard expression for the radio bremsstrahlung and a free-free Gaunt factor of 9. These coronal parameters are based on single *Einstein* and *EXOSAT* observations made a decade ago. If the coronal parameters are variable, then this estimate of the coronal radio emission will be suspect. However, the good agreement in the coronal parameters inferred by Jordan et al. (1986) from the *Einstein* observation of Procyon made on 1981 March 31 and the *EXOSAT* observation made on 1983 October 21, as well as the apparent lack of significant variability of the transition-region lines noted by Ayres (1991), suggest that the assumption of a steady level of coronal emission is reasonable.

3.4. *Emission from a Warm Wind*

The radio emission expected from the ionized component of a stellar wind can be predicted from the model of Wright & Barlow (1975) (see also Panagia & Felli 1975 and Olnon 1975 for similar analyses). Assuming an optically thick wind having an r^{-2} density law and $T_e \sim 10^4\text{–}10^5$ K, we predict

$$S_\nu(\text{wind}) = 300\ \mu\text{Jy}\ (\dot{M}_{\text{ion}}/10^{-10}\ M_\odot\ \text{yr}^{-1})^{4/3} \times (v_w/400\ \text{km s}^{-1})^{-4/3}\ ,$$

for the 3.6 cm flux density, where v_w is the wind velocity. Our steady emission level of 33 μJy corresponds to an ionized mass-loss rate $\dot{M}_{\text{ion}} = 2.0 \times 10^{-11}\ M_\odot\ \text{yr}^{-1}$, which is $\sim 10^3$ times greater than the present solar mass-loss rate. However, this value is only an upper limit to the actual ionized mass-loss rate of Procyon, since the wind is only marginally optically thick in this case. The condition for $\tau_\nu > 1$ requires that $\phi_{\text{rad}} > \phi_* =$

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5.5 mas, where $\phi_{\rm rad} = 1.38$ mas $S_\nu^{0.5}(T_e/10^4\ {\rm K})^{-0.5}$ (here S_ν is in μJy: see Drake & Linsky 1986). For the observed steady emission level of 33 μJy and an assumed wind temperature $T_e = 10^4$ K, $\phi_{\rm rad} = 8.0$ mas, so the above inequality is indeed marginally satisfied. If, however, $T_e = 10^5$ K, then $\phi_{\rm rad} = 2.5$ mas and the wind must be optically thin. In this case, the observed 33 μJy source must be a combination of stellar disk emission, coronal emission, and optically thin wind emission. If we use the minimum estimate of 8 μJy for the first component (assuming $T_b = T_{\rm eff}$), and our previous 12 μJy estimate for the coronal flux density, then the optically thin wind component can contribute only $S_\nu({\rm wind}) \leq 13$ μJy. From equation (3) of Drake & Linsky (1986), we then derive $\dot{M}_{\rm ion} \leq 1.7 \times 10^{-11}\ M_\odot\ {\rm yr}^{-1}$.

3.5. *Nonthermal Emission from Radio Bursts*

Our one detection of Procyon at 115 μJy implies that its X-band radio emission can occasionally attain a level of at least log $L_\nu = 12.23$, which is only very rarely attained on the Sun during strong type IV bursts. The standard explanation for these large solar radio bursts is that they are produced either by plasma wave (for the coherent bursts) or by gyrosynchrotron (for the broad-band components) emission mechanisms. If a similar phenomenon is responsible for the 1991 April 13 flux density value of 115 μJy, then this would imply the existence of substantial magnetic fields on Procyon.

4. DISCUSSION AND CONCLUSIONS

We have detected Procyon as a weak and apparently variable radio soure. The star was at a ~33 μJy flux density level on four out of five occasions that it was observed. This level is about that expected from a combination of the emission from its optically thick stellar disk emission (24 μJy if $T_b^X = 2 \times 10^4$ K) and its optically thin coronal emission (12 μJy). Whether the radio variability of Procyon is attributed to a varying area coverage of active regions (unlikely in our opinion) or to some type of burst or flare (more likely), in both cases we are led to the possibility that Procyon has localized magnetic fields of a strength similar to that found for solar active regions (say 0.3–2.0 kG). The existence of such magnetic regions suggests that Procyon may have an operative solar-like dynamo. This would be very interesting because, as pointed out by Simon & Drake (1989), Procyon has a $B-V$ color of 0.42 that places it precisely on the boundary line in the H-R diagram between cooler stars with well-established dynamos, which exhibit rotation-activity correlations, and the majority of early F stars that show no such correlation, and whose outer atmospheres may be heated by nonmagnetic processes. The radio data thus suggest that at least a weak or intermittent magnetic dynamo may be operating in Procyon, although this may not dominate other global heating mechanisms.

The normally very weak 33 μJy flux density of Procyon at X-band allows us to place upper limits on its present ionized mass rate of $\dot{M}_{\rm ion} \leq 2 \times 10^{-11}\ M_\odot\ {\rm yr}^{-1}$. Recently, a novel hypothesis has been proposed by Willson, Bowen, & Struck-Marcell (1987) (hereafter W87) that A–F stars are losing mass at time-averaged rates of $\dot{M} \geq 10^{-9}\ M_\odot\ {\rm yr}^{-1}$ as a result of pulsationally driven winds. Two problems with this high–mass-loss hypothesis are: (*a*) there has been no model atmosphere calculation performed in which the presence of pulsational instabilities has been shown to cause mass loss of this large order of magnitude, and (*b*) there is no observational evidence that any late A or early F dwarf stars in the solar neighborhood are losing mass at anywhere near this rate. Drake (1988) discussed point (*b*) and concluded that the observational evidence was completely consistent with very low mass loss (at a rate similar to the present solar value) for such stars: he showed that X-ray data could be used to constrain the mass loss of coronal-temperature plasma to $10^{-12.6}\ M_\odot\ {\rm yr}^{-1}$, that the 6 cm observation of Vega (A0 V) by Hollis, Chin, & Brown (1985) implied $\dot{M}_{\rm ion} < 10^{-9.5}\ M_\odot\ {\rm yr}^{-1}$, and that UV data implied upper limits to outflowing plasma at temperatures between 5×10^3 and 2×10^4 K of $10^{-10.5}$–$10^{-9.5}$ $M_\odot\ {\rm yr}^{-1}$. Furthermore, Brown et al. (1990) surveyed 17 A and F dwarf stars with the VLA at 6 cm for precisely the purpose of trying to detect the mass loss predicted by the W87 hypothesis. They present theoretical arguments in their paper that the outflow produced by pulsational driving would be substantially, if not completely, ionized, and thus should produce free-free emission at detectable levels at cm wavelengths. (In fact, an ionized mass loss rate of $10^{-9}\ M_\odot\ {\rm yr}^{-1}$ for a 10^4–10^5 K wind with an outflow velocity of 400 km s^{-1} would result in a 3.6 cm flux density of ~5.9–7.5 mJy at the distance of Procyon.) Brown et al. (1990), in fact, detected no emission from any of the stars they observed, and derived upper limits to mass loss as low as $7 \times 10^{-11}\ M_\odot\ {\rm yr}^{-1}$ for the F star Procyon, which would seem to rule out the high–mass-loss hypothesis as being viable.

More moderate mass-loss rates for mid-F stars have been proposed in a different context by Hobbs, Iben, & Pilachowski (1989), and in a later somewhat modified form by Schramm, Steigman, & Dearborn (1990), as a way of matching the pattern of observed Li abundances in F and G dwarf stars. Schramm et al. (1990) *require* that mid-to-late-F dwarf stars (on the red edge of the instability strip) suffer a time-averaged mass-loss rate of $10^{-10}\ M_\odot\ {\rm yr}^{-1}$. Yet further stellar evolutionary calculations (Sackmann, Boothroyd, & Fowler 1990; Boothroyd, Sackmann, & Fowler 1991) examining the consequences of mass loss of varying amounts on the evolution of solar-mass stars have appeared in the literature, but, to the best of our knowledge, there is no strong observational evidence for such high mass-loss rates. Our present upper limit of $2 \times 10^{-11}\ M_\odot\ {\rm yr}^{-1}$ for the admittedly rather middle-aged F star Procyon is thus inconsistent with even the moderate mass-loss hypothesis except for cases where most of the mass loss occurs at early evolutionary stages, i.e. the mass loss must be highly time-variable.

Finally, we note that the results of this radio-monitoring of Procyon program are suggestive of perhaps fairly frequent activity that might be studied in more detail in a long-term monitoring program of this star. Flaring in F and G main-sequence stars is almost certainly present, but because of the brightness of the photospheric spectrum it is almost impossible to detect in the visible region of the spectrum. Excluding close binary stars like W UMa and short-period RS CVn stars, a fairly complete literature search that we have made has found only a handful of claimed detections of optical flares in such stars (Olson 1980; Bakos 1983; Kovalchuk & Pugach 1984; Robinson & Bopp 1987; and Zhousheng, Yulan, & Xunhao 1987). While X-ray monitoring of F and G main-sequence stars might be expected to be an efficient flare-detection strategy, only one such star (π^1 UMa) has been observed to produce an X-ray flare (Landini et al. 1986), and long-term monitoring programs are probably not practicable for satellite observations like *ROSAT*. A VLA program that observed Procyon for a couple of hours, say once every 2 weeks for a year or two, has the potential of providing otherwise unobtainable information

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on activity in such a star. Also, concatenation of the data from a number of different runs should enable one to determine the reality of the weak point source to the north of Procyon, as well as the possible enveloping extended emission, that is present in the map made from the 10 hr accumulation of data that is shown in Figure 1. Another somewhat earlier spectral type star that it would be of great interest to monitor with the VLA is Sirius ($=\alpha$ CMa) which has $\phi_* = 5.7$ mas. We would expect that this A0 V star should be a quiescent radio emitter of 13 μJy due to its finite angular size and assuming $T_b = T_{\rm eff}$. It is still unclear whether a star such as Sirius that has a radiative rather than a convective envelope has any atmospheric structures such as a chromosphere or a corona, or if it has time-variable phenomena similar to solar flares. If there is a temperature reversal above its photosphere, the actual radio flux may be greater than the above-quoted minimum (photospheric) value. Thus, a deep X-band observation of Sirius could help to elucidate the present mystery about the nature of the outer atmospheres of A stars.

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