THE PHOTOSPHERIC MAGNETIC FIELD OF THE dM3.5e FLARE STAR AD LEONIS

STEVEN H. SAAR[1] AND JEFFREY L. LINSKY[2]
Joint Institute for Laboratory Astrophysics, University of Colorado and National Bureau of Standards

ABSTRACT

A high-resolution infrared spectrum of the dM3.5e flare star AD Leo, obtained with the Kitt Peak 4 m Fourier Transform Spectrometer, clearly shows the presence of strong magnetic fields. This is the first detection of photospheric fields on a dMe star. We have modeled five absorption lines in the 4400–4600 cm^{-1} (2.27–2.17 μm) region and infer that 73% $\pm$ 6% of the surface of AD Leo is covered by active regions outside of dark spots containing a mean field strength of $B = 3800 \pm 260$ G. If these active regions are brighter than the quiet photosphere, the surface filling factor will be somewhat smaller. Since simultaneous Hα observations exhibited no evidence of flares, our observations probably represent the quiescent magnetic flux level. The inferred field strength is consistent with equipartition of magnetic and thermal pressures in the photosphere (scaled from solar network fields) and is similar to values derived using the scaling laws of Golub. The large observed filling factor is consistent with efficient dynamo generation of magnetic flux in this rapidly rotating star.

Subject headings: magnetic fields — stars: atmospheres — stars: flare — stars: individual

I. INTRODUCTION

Accurate measurements of stellar surface magnetic field strengths and fractional area coverages can provide empirical constraints on such important theoretical problems as the nature of dynamos, mechanisms for nonradiative heating in outer atmospheres, and the evolution of stellar angular momentum and interior properties (Marcy 1984). Understanding magnetic properties of dMe flare stars is of particular interest, due to the enormous enhancement of their activity indicators relative to those of normal solar-like stars (see reviews in Byrne and Rodonó 1983). No positive detection of fields has ever been made for these stars, however, despite several attempts using polarization techniques (e.g., Vogt 1980; Pettersen and Hsu 1981).

The M dwarf flare stars exhibit many phenomena, including strong chromospheric and coronal emission and powerful flares, that by analogy with the Sun indicate intense magnetic fields exist in their photospheres. The greatly enhanced level of this activity relative to the Sun suggests that substantial fractions of their surfaces are covered with magnetic regions (e.g., Linsky *et al.* 1982). Because of the lack of magnetic data for M stars, and the importance of such information, we have begun a program to measure directly the field parameters of dM and dMe stars. We present in this *Letter* the first such measurement for a dMe flare star: AD Leo.

II. OBSERVATIONS AND ANALYSIS

AD Leo (= Gl 388) is an interesting target for several reasons. It is a single, dwarf M3.5e star with well-studied flare

characteristics (Pettersen, Coleman, and Evans 1984). Its large X-ray luminosity (log L_x = 29.0) places it among the upper envelope of X-ray emitting dwarfs (Golub 1983). Lang *et al.* (1983) detected highly polarized radio bursts from AD Leo and interpreted their observation as due to electron-cyclotron maser emission from electrons spiraling in coronal magnetic fields of about 250 G. The recent discovery of photometric modulation due to starspots ($P = 2^d.695$; W. Sandmann 1985, private communication) and strong chromospheric and transition region emission (Rodonó *et al.* 1984) further indicate the presence of enormous magnetic activity. Finally, since AD Leo is relatively bright (m_v = 9.4, m_K = 4.7) and has a low projected rotational velocity ($v \sin i$ = 5 km s^{-1}; Vogt, Soderblom, and Penrod 1983), it is a good candidate for magnetic line profile analysis.

We observed AD Leo in the infrared K band in unpolarized light with the KPNO 4 m Fourier Transform Spectrometer (4 m FTS; see Hall *et al.* 1979) to take advantage of the proportionality of magnetic Zeeman splitting to λ^2 and the near-infrared peak in stellar flux. Giampapa, Golub, and Worden (1983) and Gondoin, Giampapa, and Bookbinder (1985) have also used the 4 m FTS for stellar magnetic observations. We used a narrow-band interference filter covering 4400–4600 cm^{-1} (2.27–2.17 μm) to increase the signal-to-noise (S/N) ratio. A 6 hr exposure of AD Leo taken in poor seeing conditions ($\sim$ 5$''$) yielded a spectrum with a S/N $\approx$ 25 at an apodized resolution of 0.1 cm^{-1} ($\lambda/\Delta\lambda$ = 45,000). Our data thus represent a spatial and temporal average over $\approx$ 9% of the stellar rotational period.

The raw spectrum was divided by a tungsten lamp exposure to remove the filter response, and by a spectrum of Sirius which had been logarithmically scaled to the same average airmass as AD Leo to remove telluric lines. We then visually compared a multiplet of Ti I lines in this reduced spectrum with umbra/photosphere ratio profiles in Hall's (1973) in-
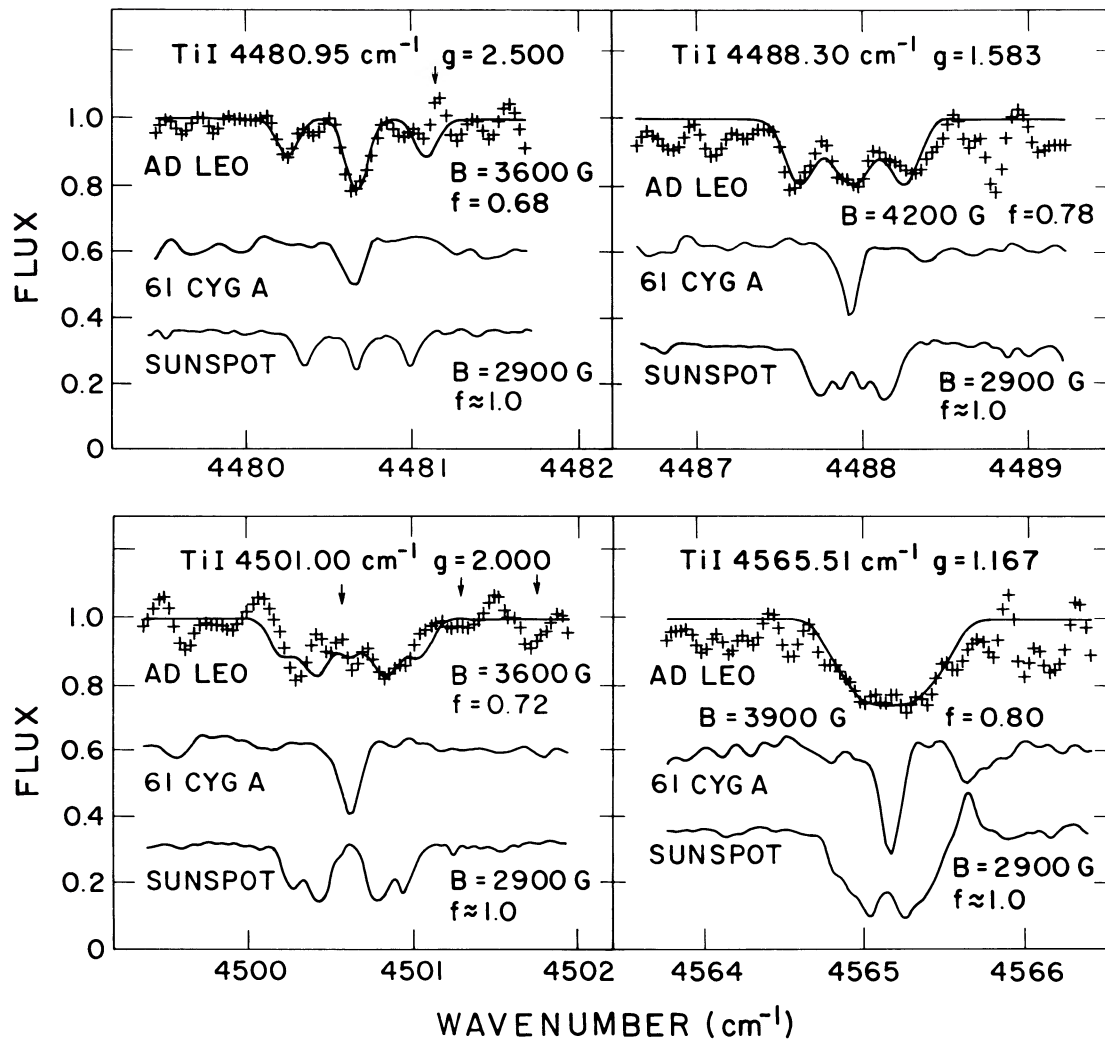
FIG. 1.—Comparison of apodized 4 m FTS spectra of AD Leo (*crosses*), similar spectra of the dK5 magnetically inactive star 61 Cyg A, and a sunspot umbra/photosphere ratio spectrum from Hall's (1973) atlas. (The ratio spectrum removes telluric lines without affecting Ti I, which is absent at solar photospheric temperatures.) The solid line model to the AD Leo data is for the magnetic parameters indicated. All data are on the wavenumber scale of AD Leo. The spectra have been displaced vertically for clarity, and positions where the noise is enhanced because of the approximate removal of strong telluric lines from the AD Leo spectrum are marked with arrows.

frared sunspot atlas (for which the umbral field strength was 2900 G [Hall 1970]) and unsplit profiles of the inactive K5 dwarf 61 Cyg A which we also observed (see Fig. 1). Inspection of these profiles suggests that fields well in excess of 3000 G cover much of the photosphere of AD Leo.

Visual inspection of the spectrum, however, also reveals numerous line blends in this region, which complicate the analysis and can lead to spurious Zeeman signals. As a detailed synthesis of these largely unidentified lines is not now possible, we plan in the future to observe a chromospherically inactive star of the same spectral type and employ a differential analysis (see Saar, Linsky, and Beckers 1985, hereafter SLB) to remove the effects of blends. For the present, however, we analyze the spectrum without compensating for blends and rely on the consistency of the measured field parameters among several modeled lines to argue that the deduced Zeeman signal is not caused by the chance positioning of extraneous lines in the spectrum (cf. Gray 1984).

We computed theoretical line profiles using our LTE magnetic modeling code (SLB; S. H. Saar 1985, in preparation), which includes radiative transfer effects such as line saturation, and computes the full Zeeman patterns. Since no adequate magnetically insensitive lines lie in this spectral region, we could not compare low and high g lines directly (cf. Robinson 1980; Marcy 1984). Instead, we computed models for each line individually, assuming $v \sin i = 5$ km s^{-1}, a macroturbulent velocity $\zeta = 3$ km s^{-1} (Vogt, Soderblom, and Penrod 1983), and pure LS coupling for the Zeeman splitting (Beckers 1969). The angle γ between the magnetic field and the line of sight was taken to be a disk-averaged value (Marcy 1982; for a limb darkening coefficient of 0.3) of $\langle \gamma \rangle = 43°$. We then varied the line opacity ratio (η), magnetic field strength (B), and magnetic area filling factor (f) for each model to match the observed profiles. The code combines LTE magnetic (F_{mag}) and nonmagnetic flux profiles (F_{quiet}) in the form $F_{\mathrm{total}} = f F_{\mathrm{mag}}(\eta, B) + (1 - f) F_{\mathrm{quiet}}(\eta, 0)$, assuming

TABLE 1

SPECTRAL LINES USED AND DERIVED PARAMETERS

ATOM AND WAVENUMBER[a] (cm^{-1})	TRANSITION[a]	g_{eff}[b]	NORMALIZED[c] LOG gf	DERIVED PARAMETERS		
				Normalized η	f	B (gauss)
Ti I 4480.95	$^5P_1-^5D_0^0$	2.500	$\equiv 1$	$\equiv 1$	0.68	3600
Ti I 4488.30	$^5P_3-^5D_3^0$	1.583	2.3	1.7	0.78	4200
Ti I 4496.61[d] ...	$^5P_2-^5D_2^0$	1.667	2.9	≈ 2.8	≈ 0.66	≈ 3700
Ti I 4501.00	$^5P_1-^5D_1^0$	2.000	2.3	2.6	0.72	3600
Ti I 4565.51	$^5P_2-^5D_3^0$	1.167	4.8	4.6	0.80	3900

[a] From Hall 1973.
[b] From Beckers 1969.
[c] From Kurucz and Petreymann 1975.
[d] The 4496.61 cm^{-1} line is heavily blended, and its derived parameters are poorly determined. Lower weight is given to these results.

identical continuum and line properties for the magnetic and quiet regions. The computed models (Fig. 1) indicate that active regions with a mean field strength of 3800 $\pm$ 260 G cover 73% $\pm$ 6% of the surface of AD Leo (Table 1). The relative opacity ratios computed from our fits compare well with those of Kurucz and Peytremann (1979), and the B and f values are uncorrelated with other parameters, confirming that our line models are reasonable. The stated errors reflect the scatter of the individual magnetic parameters from the mean. Deviations of the magnetic parameters in the individual line models from the mean can be accounted for by line blends, noise, inadequate removal of telluric lines (e.g., the 4480 cm^{-1} line), and departures from LS coupling (Giampapa, Golub, and Worden 1983).

A simultaneous, serendipitous observation of Hα, kindly provided by Dr. B. Bopp, shows a normal equivalent width of 2.88 Å (cf. Bopp and Schmitz 1978; Giampapa et al. 1978) and a central reversal, indicating that no major flare activity occurred during the middle hour or so of the FTS exposure. Since large flares are rare (Pettersen, Coleman, and Evans 1984), we presume that our magnetic measurements probably represent the normal, "quiescent" magnetic flux level of AD Leo.

III. DISCUSSION

We first consider the type of active regions detected. The value of 73% for the fractional magnetic area coverage was derived assuming equal continuum fluxes in the magnetic and nonmagnetic regions. If we now consider the possible contribution of starspots and assume $T_{\mathrm{spot}}/T_{\mathrm{eff}} = 0.85$ (Vogt's 1983 value for the dM0e flare star BY Dra) and T_{eff}(AD Leo) = 3350 K (from Table 2 of Pettersen 1983 for $V - K = 4.8$), we find the continuum Planck function ratio F_λ(spot)/F_λ(photosphere) = 0.7 at 2.2 μm. Thus if the observed magnetic regions are starspots, they must cover 0.73/0.7, or the entire stellar surface, clearly an unphysical result. Indeed, only recently (W. Sandmann 1985, private communication) has any evidence for spots on AD Leo been found (Bopp and Espenak 1977, for example, saw no photometric modulation). We therefore presume that the magnetically split lines are formed in regions which are roughly as bright as the quiet photo-

sphere, as we found (SLB) for the dK5e flare star EQ Vir, and as is found in the magnetically active solar network and plages. If the magnetic regions are brighter than the quiet photosphere, our derived filling factor of 0.73 will be somewhat too large.

The field strength we obtain is about one-half of Mullan's (1975) predicted value (based on scaling arguments from his starspot models), but is consistent with equal gas and magnetic pressures in the stellar photosphere when scaled from solar network fields. We interpolate between Mould's (1976) M dwarf model atmospheres ($T_{\mathrm{eff}} = 3250$ K and 3500 K, log $g = 4.75$) to find that the photospheric pressure at $\tau_{\mathrm{Rosseland}} = 1$ is $P_{\mathrm{AD\,Leo}} = 7.57 \times 10^5$ dyn cm^{-2}. Then using $P_\odot = 1.173 \times 10^5$ dyn cm^{-2} (at $\tau_{5000} = 1$; Vernazza, Avrett, and Loeser 1981) and a solar network field strength of 1500 G (Tarbell and Title 1977), we assume equipartition and derive $B_{\mathrm{AD\,Leo}} = (P_{\mathrm{AD\,Leo}}/P_\odot)^{1/2} \times B_\odot = 3810$ G, in excellent agreement with our observed value of 3800 G. EQ Vir, the only other flare star with a measured photospheric magnetic field, also has a field (2500 $\pm$ 300 G) close to equipartition (SLB).

We compare our magnetic parameters with estimates based on Golub's (1983) coronal loop scaling laws (note the incorrect exponents in his equations):

$$B = 1.2 \times 10^{-8}(v_{\mathrm{twist}}/v_\odot)^{-1}\left[T_c^3(g_*/g_\odot)\right]^{1/2} \quad (1)$$

and

$$f = 3.4 \times 10^{-9}F_x/P(T)\left[T_c^3(g_*/g_\odot)\right]^{-1}, \quad (2)$$

where $P(T)$ is the plasma emissivity given by $P(T) = F_x/H_c n_e^2 f_c$, F_x is the stellar X-ray surface flux ($= L_x/4\pi R_*^2$), T_c is the coronal temperature, v_{twist} is the magnetic footpoint twisting velocity, f_c is the magnetic filling factor at the base of the corona, and H_c is the coronal emission scale height. The stellar coronal loops are assumed to have lengths $L = H_c = 5 \times 10^3 T_c \times (g_*/g_\odot)^{-1}$. Taking $R_* = 0.43R_\odot$ (Pettersen 1980), log $g = 4.17 + 0.38(B - V)$ (Gray 1976), log $L_x = 29.0$, $T_c = 7 \times 10^6$ K (Swank and Johnson 1982; note the L_x and T_c data are not cotemporal with ours), $v_{\mathrm{twist}}/v_\odot = 1/3$ (L. Golub 1985, private communication), $n_e = 10^{10}$ cm^{-3}, and $f_c = 0.73$,

we find B(model) = 945 G and f(model) = 6.33. This type of result ($f > 1$), Golub suggests, implies that the loop structures on AD Leo must be smaller than assumed (i.e., $L < H_c$). There is no obvious lower limit on L, however. If we instead force f(model) to agree with the observed value of 0.73, we find B(model) = 2780 G, which is lower than the observed value of 3800 G but within the errors of the input parameters. For example, if we set $n_e = 1.37 \times 10^{10}$ cm^{-3}, we find B(model) = 3800 G for f(model) = 0.73. We therefore conclude that Golub's models can yield magnetic field parameters in reasonable agreement with our results.

The high-temperature coronal component of AD Leo ($T_c \approx 4 \times 10^7$ K) obtained by Swank and Johnson (1982) from modeling *Einstein* SSS data may correspond to coronal regions above areas of even larger magnetic pressures, such as starspots (e.g., Giampapa, Golub, and Worden 1983). Substitution of this higher temperature into the model yields B(model) = 12,900 G and f(model) = 0.19. If such parameters describe starspots, this component of AD Leo's magnetic surface structure would have escaped detection at our S/N, since the depth of the resulting starspot sigma components with a 19% filling factor would be less than $\approx 3\%$. Higher S/N data are therefore needed to determine whether very large fields (≥ 10 kG) are present in spot umbrae on AD Leo.

Our results for AD Leo imply that the surface-averaged field $\langle B \rangle \equiv fB \approx 2800$ G. This averaged field strength, together with that of EQ Vir (with $\langle B \rangle = 2000$ G), is well above the mean detected in active dwarfs to date of $\langle B \rangle = 600$–700 G (SLB; Gray 1985). Gray suggests that the small range of $\langle B \rangle$ for the observed stars ($\sigma \approx 100$ G) is due to the existence of a universally constant number of magnetic flux tubes on active stars. Our results for AD Leo and EQ Vir indicate that at least the most active and/or the coolest stars (the BY Dra and dMe stars) deviate significantly from the apparent trend.

Although the sample is small, the large surface-averaged fields of AD Leo and EQ Vir appear to reinforce the idea that rapid rotation is central to stellar magnetic activity. With rotational periods of $2\overset{d}{.}695$ and $3\overset{d}{.}96$ (Vogt *et al.* 1983), respectively, AD Leo and EQ Vir have much larger angular velocities than any other late-type star with measured magnetic fields. The field strengths in the nonspotted regions of these flare stars, however, seem to be controlled by the photospheric pressure balance. Perhaps the large observed filling factors, therefore, are due to redistribution of the emerging magnetic flux to cover a larger surface area when surface field *strengths* have reached maxima (Galloway and Weiss 1981) at the equipartition value. If this scenario is correct, we anticipate that f will increase with angular velocity for stars with equipartition field strengths, since simple dynamo models predict magnetic flux generation scales with rotation (e.g., Durney and Robinson 1982). The theory of Durney and Robinson (1982) in fact predicts $f \approx 1.0$ (assuming equipartition fields) for stars with $T_{\rm eff}$ and Ω values appropriate for AD Leo and EQ Vir, in rough agreement with our results. The weak correlation of filling factor with rotational velocity noted by Gray (1985) is also consistent with this concept.

We conclude that the surface magnetic fields on the dM3.5e flare star AD Leo have characteristics very similar to those found on the dK5e flare star EQ Vir, namely field strengths consistent with thermal pressure balance in the photosphere, and filling factors consistent with rapid rotation. Further measurements of the magnetic parameters of M dwarfs are needed to help delineate exactly how magnetic flux generation varies with stellar parameters.

REFERENCES

Beckers, J. M. 1969, *A Table of Zeeman Multiplets* (AFCRL 115).
Bopp, B. W., and Espenak, F. 1977, *A.J.*, **82**, 916.
Bopp, B. W., and Schmitz, M. 1978, *Pub. A.S.P.*, **90**, 531.
Byrne, P. B., and Rodonó, M. 1983, eds., *IAU Colloquium 71, Activity in Red Dwarf Stars* (Dordrecht: Reidel).
Durney, B. R., and Robinson, R. D. 1982, *Ap. J.*, **253**, 290.
Galloway, D. J., and Weiss, N. O. 1981, *Ap. J.*, **243**, 945.
Giampapa, M. S., Golub, L., and Worden, S. P. 1983, *Ap. J.*, **268**, L121.
Giampapa, M. S., Linsky, J. L., Schneeberger, T. J., and Worden, S. P. 1978, *Ap. J.*, **226**, 144.
Gondoin, P., Giampapa, M. S., and Bookbinder, J. A. 1985, *Ap. J.*, **297**, 710.
Golub, L. 1983, in *IAU Colloquium 71, Activity in Red Dwarf Stars*, ed. P. B. Byrne and M. Rodonó (Dordrecht: Reidel), p. 83.
Gray, D. F. 1976, *The Observation and Analysis of Stellar Photospheres* (New York: Wiley).
———. 1984, *Ap. J.*, **277**, 640.
———. 1985, *Pub. A.S.P.*, **97**, 719.
Hall, D. N. B. 1970, Ph.D. thesis, Harvard University.
———. 1973, *An Atlas of Infrared Spectra of the Solar Photosphere and of Sunspot Umbrae* (Tucson: Kitt Peak National Observatory).
Hall, D. N. B., Ridgway, S., Bell, E. A., and Yarborough, J. M. 1979, *Proc. Soc. Photo-Opt. Instr. Eng.*, **172**, 121.
Kurucz, R. L., and Peytremann, E. 1975, *A Table of Semiempirical gf Values, Part 3* (*Smithsonian Ap. Obs. Spec. Rept. 362*).

Lang, R. R., Bookbinder, J., Golub, L., and Davis, M. M. 1983, *Ap. J.*, **272**, L15.
Linsky, J. L., Bornmann, P. L., Carpenter, K. G., Wing, R. F., Giampapa, M. S., Worden, S. P., and Hege, E. K. 1982, *Ap. J.*, **260**, 670.
Marcy, G. W. 1984, *Ap. J.*, **276**, 286.
Mould, J. R. 1976, *Astr. Ap.*, **48**, 443.
Mullan, D. J. 1975, *Astr. Ap.*, **40**, 41.
Pettersen, B. R. 1980, *Astr. Ap.*, **82**, 53.
———. 1983, in *IAU Colloquium 71, Activity in Red Dwarfs*, ed. P. B. Byrne and M. Rodonó (Dordrecht: Reidel), p. 18.
Pettersen, B. R., Coleman, L. A., and Evans, D. S. 1984, *Ap. J. Suppl.*, **54**, 375.
Pettersen, B. R., and Hsu, J.-C. 1981, *Ap. J.*, **247**, 1013.
Robinson, R. D. 1980, *Ap. J.*, **239**, 961.
Rodonó, M., *et al.* 1984, in *Proc. of the 4th European IUE Conference*, ed. E. Rolfe and B. Battrick (ESA SP-218), p. 247.
Saar, S. H., Linsky, J. L., and Beckers, J. M. 1985, *Ap. J.*, in press (SLB).
Swank, J. H., and Johnson, H. M. 1982, *Ap. J.*, **259**, L67.
Tarbell, T. D., and Title, A. M. 1977, *Solar Phys.*, **52**, 31.
Vernazza, J. E., Avrett, E. H., and Loeser, R. 1981, *Ap. J. Suppl.*, **45**, 635.
Vogt, S. S. 1980, *Ap. J.*, **240**, 567.
———. 1983, in *IAU Colloquium 71, Activity in Red Dwarfs*, ed. P. B. Byrne and M. Rodonó (Dordrecht: Reidel), P. 137.
Vogt, S. S., Soderblom, D. R., and Penrod, G. D. 1983, *Ap. J.*, **269**, 250.

JEFFREY L. LINSKY and STEVEN H. SAAR: Joint Institute for Laboratory Astrophysics, University of Colorado, Mail Code 440, Boulder, CO 80309