The Astronomical Journal, 125:868–874, 2003 February

FAR-ULTRAVIOLET OBSERVATIONS OF THE CIRCUMSTELLAR GAS IN THE 2 ANDROMEDAE SYSTEM

K.-P. Cheng[1,2]
Department of Physics, California State University at Fullerton, P.O. Box 6866, Fullerton, CA 92834; kcheng@fullerton.edu

and

James E. Neff[1,2]
Department of Physics and Astronomy, College of Charleston, 101 Science Center, 58 Coming Street, Charleston, SC 29424; neffj@cofc.edu
Received 2002 August 15; accepted 2002 October 22

ABSTRACT

The A5 star β Pictoris is a possible young planetary system and has the best-studied circumstellar disk. Our visible and ultraviolet observations of 2 Andromedae indicated that this A3 star has β Pictoris–like gas infall. We present the far-ultraviolet spectrum (905–1195 Å) of 2 And we obtained with the NASA-CNES-CSA *Far Ultraviolet Spectroscopic Explorer* (*FUSE*). Unlike β Pic, 2 And's *FUSE* spectrum does not show strong chromospheric emission lines from C III and O VI. However, 2 And's *FUSE* spectrum contains many non-photospheric lines that allow us to probe the circumstellar gas. For example, between 1120 and 1140 Å, we detected several Fe III absorption lines arising from hyperfine levels of ground state, which cannot be formed in the interstellar medium. These lines are good diagnostics of the circumstellar gas. We also detected circumstellar Fe II, Cr III, Mn III, and O I (^1D) lines. The simultaneous presence of these species suggests that the circumstellar environment of 2 And could include regions with different temperatures and densities.

Key words: circumstellar matter — planetary systems: protoplanetary disks — stars: individual (2 Andromedae)

1. INTRODUCTION

β Pictoris (A5 V) has been known for more than a decade as a planetary system candidate with circumstellar dust and gas disks. It has been suggested that the short-term variations of circumstellar gas absorption components observed in β Pic's spectra could be due to the evaporation of comet-size bodies (Beust et al. 1990) passing close to the star. It also has been suggested that the huge dust disk around β Pic could be an analog of our Kuiper belt, a region past the orbit of Neptune that is now considered to be the source of short-period comets. Recent *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) observations of β Pic revealed broad emission lines due to highly ionized species, C III and O VI, which might originate from a solar-like extended chromosphere (Deleuil et al. 2001; Bouret et al. 2002).

We have been searching for β Pictoris–like systems in a volume-limited sample of 62 nearby A stars. Our study included two independent searches: one for circumstellar dust using *Infrared Astronomy Satellite* (*IRAS*) data (Cheng et al. 1992) and the other for circumstellar gas by using high-resolution and high signal-to-noise visual and ultraviolet spectra (Cheng, Neff, & Bruhweiler 1995). We found that more than 18% of the nearby A stars have circumstellar dust and more than a dozen have circumstellar gas. Our further monitoring of Ca II K and Na I D lines has revealed that at least four of these stars have β Pic–like variable spectral signatures indicating gaseous infall. Among them, 2 Andromedae (Table 1) is the most interesting object (Cheng, Bruhweiler, & Neff 1997).

2 And (A3 V) is a noninteracting visual binary (ADS 16467AB) with a period of 76.6 yr, a semimajor axis of 0''.277, and a visual magnitude difference of 3.7 mag (Baize & Petit 1989). The parallax measured by *Hipparcos* (ESA 1997) corresponds to a distance of 107 pc, which is much greater than the previous estimate of 19 pc listed the Bright Star Catalogue. At 107 pc, a separation of 0''.277 corresponds to about 30 AU. 2 And's companion is possibly a δ Scuti variable with a late A or early F dwarf spectral type. Although our visual, UV, and far-ultraviolet (FUV) observations of 2 And contain light from both components, the fainter companion does not make a significant contribution to the observed spectra of 2 And. The flux ratio is about 40 in the Ca II K line and even greater in the UV and FUV wavelength range.

1.1. *Previous Observations of 2 And*

Unlike β Pic, 2 And has no detectable infrared excess based on the *IRAS* data (Cheng et al. 1992), which indicates very little or no dust around 2 And. During our ground-based spectroscopic survey of nearby A stars, we detected variable redshifted Ca II K absorption features from 2 And, similar to those frequently seen from β Pic. In our initial study of 2 And (Cheng et al. 1997) we presented high-resolution, high signal-to-noise Ca II K spectra at three epochs. A transient absorption feature at +25 km s^{-1} was seen in 1994 September but not in 1993 July or 1996 August (Fig. 1). An absorption feature at +6 km s^{-1} was always present, but variable in shape. Features at −15 and −8 km s^{-1} are presumably interstellar. We also obtained ultraviolet spectra with the *International Ultraviolet Explorer* (*IUE*)

[1] Guest Observer, National Solar Observatory, KPNO, NOAO, which is operated by AURA, Inc., under cooperative agreement with National Science Foundation.

[2] Guest Observer, McDonald Observatory, University of Texas.

TABLE 1
BASIC DATA FOR 2 ANDROMEDAE

Datum	Value
Identifiers	HD 217782, HR 8766
Spectral type	A3 V[a]
m_V	5.093
$B-V$	0.094
$E(B-V)$	0.003
$T_{\rm eff}$	9000 K[b]
$\log g$	4.0
$v_{\rm rot} \sin i$	190 km s^{-1}
Radial velocity	+2 km s^{-1}
Distance (BSC)	19 pc
Revised distance (*Hipparcos*)	107 pc
Galactic coordinates	102.52–15.76

[a] As discussed in the text, the true spectral type is probably earlier than this classification from Cowley et al. 1969.
[b] As discussed in the text, the true effective temperature is probably higher (10,000 K).

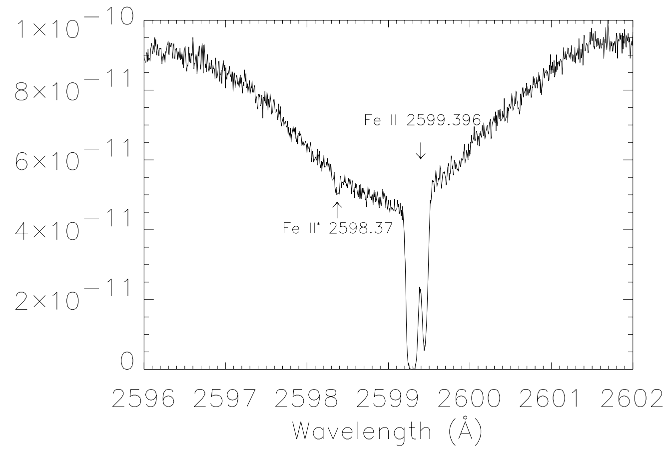

FIG. 2.—*HST* GHRS (ECH-B) spectrum of 2 And. The blended absorption lines seen in the core of the Fe II 2599.396 Å photospheric absorption feature could be partly of interstellar and circumstellar origin. The weaker absorption component on the right matches the Ca II feature at +6 km s^{-1}. The stronger component could be a blend of features at −8 and −15 km s^{-1} and is saturated. The Fe II 2598.37 Å feature can be formed only at densities higher than 10^3 cm^{-3}; therefore it must be of circumstellar origin (from Cheng et al. 1997).

and the *Hubble Space Telescope* Goddard High Resolution Spectograph (*HST* GHRS) to better measure the properties of circumstellar and interstellar gas along the line of sight toward 2 And (Fig. 2). We detected Fe II and Al III circumstellar absorption lines in our *HST* GHRS spectra (Cheng et al. 1997), similar to those observed in the β Pic system (Beust et al. 1994).

We have continued to monitor the Ca II behavior of 2 And. Repeated spectroscopic observations of Ca II absorptions has allowed us to better constrain the variability recurrence timescales of the circumstellar features (Neff, Cheng, & Meiring 2003). The feature at +6 km s^{-1} is highly variable in shape and equivalent width. The +25 km s^{-1} feature has not repeated, though there is some suggestion of a weak feature recurring around +40 km s^{-1} at several epochs. The presumably interstellar features have remained stable. These ground-based high-resolution spectra permit detailed studies of circumstellar dynamics, but they provide little information on the temperature and density structure of the circumstellar gas. For this we need high-resolution FUV spectra, which contain many diagnostics of the warm circumstellar gas.

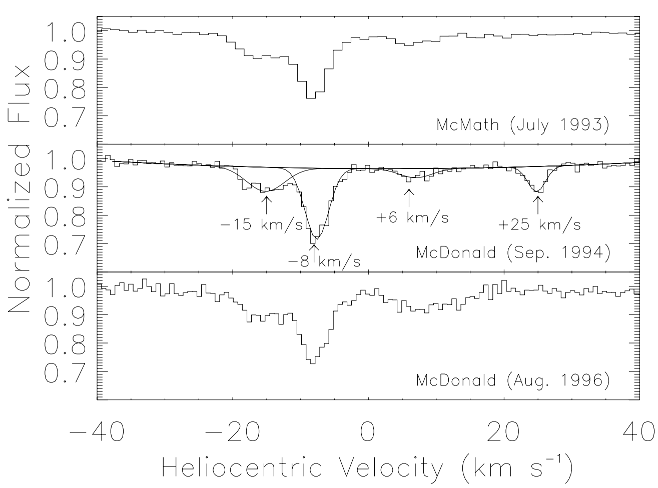

FIG. 1.—High-resolution Ca II spectra of 2 And. Spectra were obtained at the McMath-Pierce telescope in 1993 July (*top*) and at the McDonald Observatory 2.7 m telescope in 1994 September (*middle*) and 1996 August (*bottom*). We interpret the variable feature at +25 km s^{-1} as gaseous infall. This feature was present on spectra obtained two nights apart in 1994 September but was not seen at the other epochs. The broad Ca II feature at +6 km s^{-1} is circumstellar and variable but always present. (from Cheng, Bruhweiler, & Neff 1997).

1.2. *Is 2 And a β Pic–like System?*

The term "β Pic–like system" has sometimes been used to refer to objects from which stable and/or transient redshifted circumstellar absorptions are detected spectroscopically. By this definition, 2 And is a β Pic–like system. Furthermore, there are other similarities between β Pic and 2 And (Table 2). For example, they both have been identified as A-shell stars, and both have been classified as λ Bootis stars.

A-shell stars are characterized by the coexistence of two types of line profiles in their spectra: one originating in the stellar photosphere and the other one originating in the cooler shell. While the former lines are broad, the latter are sharp and narrow. Usually Ca II and Fe II absorption lines show this shell characteristic (see Figs. 1 and 2). Based on this criterion β Pic (Slettebak 1982) and 2 And (Hauck & Jaschek 2000) have both been identified as A-shell stars. Many questions are still open concerning these shell stars,

TABLE 2
2 ANDROMEDAE VERSUS β PICTORIS

Datum	2 And	β Pic
Spectral type	A3 V	A5 V
V magnitude	5.09	3.86
High $v \sin i$ (km s^{-1})	190	139
A-shell star	Yes	Yes
λ Bootis star	Yes	Yes
Circumstellar gas	Yes	Yes
Circumstellar Al III	Yes	Yes
Spectroscopic variability	Yes	Yes
Circumstellar dust	No	Yes
Age (Myr)	Unknown	12^{+8}_{-4}

including their evolutionary status. Hauck & Jaschek (2000) found that the majority of A-shell stars are well above the main sequence. The newly revised *Hipparcos* distance of 2 And ($d = 107$ pc) is more than 5 times greater than the value given in the Bright Star Catalog ($d = 19$ pc). It is possible that the A3 V spectral type needs to be revised to reflect the much higher luminosity (25 times greater than previously thought).

Most of the current theories suggest that the λ Bootis phenomenon originated from interaction between the stellar surface and its local environment. 2 And was proposed by Parenago (1958) as a λ Bootis star and was later confirmed by Andrillat, Jaschek, & Jaschek (1995). β Pic has also been classified as a λ Bootis star (King & Patten 1992). The λ Bootis stars are a class of metal-poor Population I A-type stars. Although the prototype was described by Morgan, Keenan, & Kellman (1943), the definition as a separate class among chemically peculiar stars is still controversial. Not all the λ Bootis star classifications are based on the same criteria. For example, Paunzen et al. (1997) defined λ Bootis stars as Population I hydrogen-burning, metal-poor (except for C, N, O, and S) A-type stars. This definition does not depend on phenomenological features, such as flux depressions (e.g., the 1600 Å drop), color excesses, $v \sin i$ values, etc. However, the presence of detectable amounts of circumstellar gas as seen in 2 And and β Pic is rare among chemically normal A stars (Holweger & Rentzsch-Holm 1995). Venn & Lambert (1990) suggest that the λ Bootis phenomenon might be caused by accretion of depleted circumstellar gas. Therefore, λ Bootis stars challenge our understanding of diffusion and accretion processes related to stars and their circumstellar environment.

Despite the similarities, in some ways 2 And is not like β Pictoris. The major difference is that 2 And has no detectable circumstellar dust. The variable circumstellar gas seen in the β Pic system is "second generation" material from remnant planetesimals or comets. The "evaporating comet" mechanism developed for β Pic (Beust et al. 1990) cannot be used to explain the infalling circumstellar gas in the dust-free system 2 And. To probe the origin of the infalling circumstellar gas in 2 And, we obtained new observations with the *Far-Ultraviolet Spectroscopic Explorer* satellite.

2. *FUSE* OBSERVATIONS

We observed 2 Andromedae with *FUSE* on 2001 July 3–4 in 11 exposures with a total exposure time of 21,289 s through the LWRS ($30'' \times 30''$) aperture. The *FUSE* spectrograph was described in detail by Moos et al. (2000). The observed spectra cover the 905–1185 Å wavelength range. Our data were calibrated with version 1.8.7 of the CALFUSE pipeline processing software. We corrected the wavelength scale for the heliocentric velocity error in this version of the CALFUSE software.[3] The relative accuracy of the calibrated wavelength scale is ± 9 km s^{-1}. We produced a co-added spectrum in the LiF 1B and LiF 2A channels (covering the 1100 to 1180 Å region) by cross-correlating the 11 individual exposures and doing an exposure time–weighted average flux. The final co-added spectra have a signal-to-noise ratio in the stellar continuum near 1150 Å of about 20. To obtain an absolute wavelength calibration, we cross-correlated our observed spectra with a model spectrum (described in § 3.2) to obtain the best fit for the photospheric C I lines. Because the photospheric lines are very broad, this yields an absolute accuracy for the wavelength scale of about ± 15 km s^{-1}. We then rebinned 5 original pixels to yield the optimal sampling of 0.033 Å for each new pixel, because the calibrated spectra oversample the spectral resolution for *FUSE* with the LWRS ($R = 20{,}000 \pm 2{,}000$; see *FUSE* Observer's Guide, Version 4.0.1).

3. ANALYSIS OF *FUSE* SPECTRUM OF 2 AND

3.1. *Comparison with Other Early A-Type Stars*

Based on *Voyager* ultraviolet spectrometer observations, Chavez, Stalio, & Holberg (1995) found that A stars can show a significant difference in the FUV flux level among stars of the same spectral type. However, not many A stars have been observed with *FUSE* or other high-resolution FUV instruments. We therefore compared our *FUSE* spectrum of 2 And (A3 V) with the *ORFEUS* BEFS spectrum of Vega (A0 V) and the Hopkins Ultraviolet Telescope (HUT) spectrum of β UMa (A1 V), which we retrieved from the Multimission Archive at Space Telescope. Despite the different spectral resolutions and sensitivities of the different instruments, these three early A-type stars, with different $v \sin i$, have a remarkably similar photospheric flux distribution in the FUV (Fig. 3). At the short-wavelength end, the photospheric flux drops rapidly and becomes almost negligible shortward of 1110 Å, consistent with the effective temperature of early A-type stars. At the long-wavelength end, an apparent continuum drop is clearly present in all three

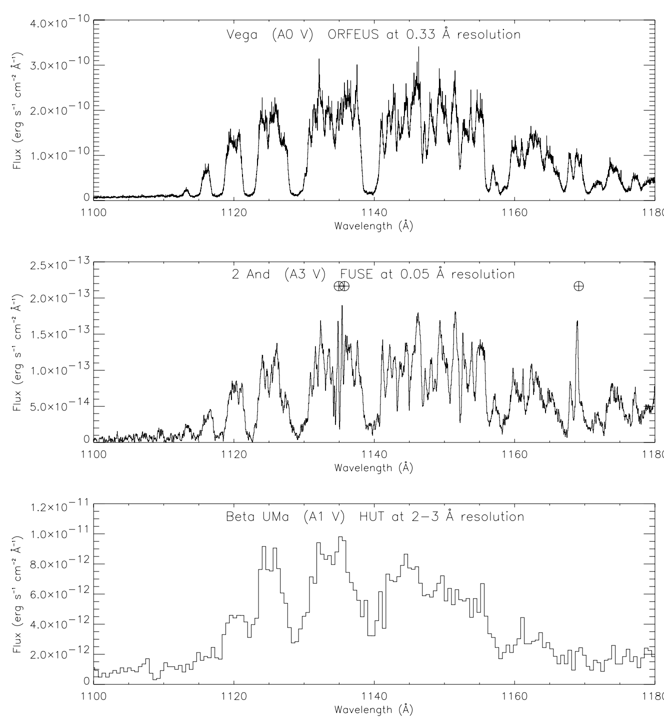

FIG. 3.—Far-UV spectra of three early A-type stars. *Middle*, Our *FUSE* spectrum of 2 And, with geocoronal and dayglow emission lines marked. For comparison, quick-look archival spectra of Vega (*top*) and β UMa (*bottom*) obtained with different instruments.

[3] See A. Fullerton 2000, Analysis of Velocity Corrections in CALFUSE 1.8.7, http://fuse.pha.jhu.edu.

spectra (Fig. 3). This apparent continuum drop is due to the H I Lyα absorption line at 1216 Å, which is very strong in stars of spectral type B3 and later. All three spectra are dominated by very strong photospheric C I absorption lines (e.g., around 1118, 1122, 1129, 1140, and 1158 Å), which appear to be saturated in the Vega spectrum.

3.2. *Comparison with Stellar Model Atmosphere Fluxes*

We did not expect the far-ultraviolet spectrum of an A3 V star (2 And) to be so similar to that of an A0 V star (Vega). We suspect that the true spectral type of 2 And is earlier and its effective temperature is consequently higher. To more accurately determine the effective temperature of 2 And, we have compared the *IUE* and *FUSE* spectra of 2 And with various model spectra generated using Kurucz models and SYNSPEC (Hubeny, Lanz, & Jeffery 1994).

Sasseen et al. (2002) found good agreement between their average FUV extinction curve, derived from *ORFEUS* spectra, and an extrapolation from the UV part of the Savage & Mathis (1979) curve. We therefore applied the Savage & Mathis (1979) extinction curve to 2 And's ultraviolet and FUV spectrum. The interstellar reddening toward 2 And is very low, $E(B-V) = 0.003$, so the correction is very small.

Because *IUE* has a well-determined absolute flux calibration, we used the *IUE* SWP spectrum of 2 And to derive a best-fit Kurucz model with $T_{\rm eff} = 10{,}000$ K (Fig. 4, *gray histogram*). However, a Kurucz model at this effective temperature substantially underestimates 2 And's FUV continuum, while the SYNSPEC model with $T = 10{,}000$ K, $\log g = 4$, and $v_{\rm rot} = 190$ km s^{-1} (Fig. 4, *smooth gray line*) slightly overestimates the FUV continuum. Our *FUSE* spectrum of 2 And shows continuum flux down to at least 1000 Å at a level that substantially exceeds that predicted by the SYNSPEC model (Fig. 4). The C I edge (1101 Å) causes the model flux to drop by several orders of magnitude, but a much less pronounced drop is seen in the 2 And *FUSE* spectrum. Our photospheric model includes strong broad absorption lines from C I, N I, and Fe II that closely match the observed *FUSE* spectrum.

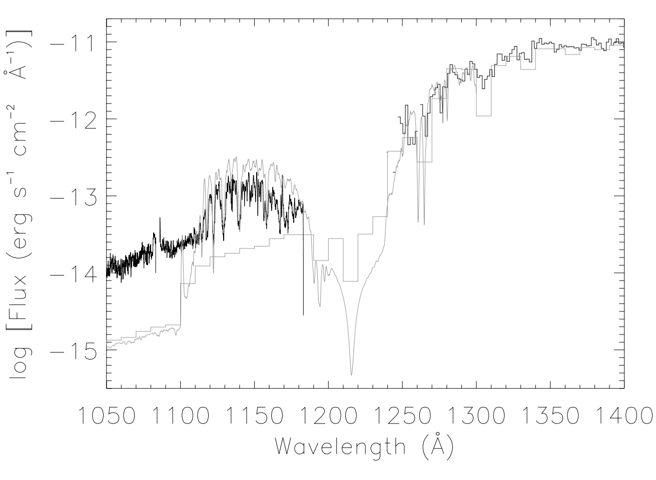

FIG. 4.—Comparison of 2 And's observed (*dark lines*) UV (>1250 Å, from *IUE*) and FUV (<1180 Å, from *FUSE*) with synthetic spectra (*smooth gray line*: from SYNSPEC with $T = 10{,}000$ K, $\log g = 4$, and $v_{\rm rot} = 190$ km s^{-1}; *gray histogram*: Kurucz atlas with same parameters). The model spectra are scaled to match the *IUE* flux. Prominent features of the model spectrum include the extreme H I Lyα absorption around 1216 Å, C I absorption lines in the *FUSE* range, and the C I edge at 1101 Å.

3.3. *Comparison with β Pic and 51 Oph*

Despite having similar spectral characteristics in every other wavelength region we have studied (see § 1.2), the far-ultraviolet spectra of 2 And and β Pic have almost nothing in common (see Fig. 5). The most obvious features of the *FUSE* spectrum of β Pic are the broad O VI and C III emission lines (Deleuil et al. 2001). Bouret et al. (2002) demonstrated that these lines could be reproduced by a simple model involving a chromosphere and transition region. Although our *FUSE* spectrum of 2 And does show C III emission lines, they were confined to the aperture and were seen only during the daytime intervals of the *FUSE* observations, implying that the emission is caused by scattered solar emission. Other emission features visible at 1134 and 1168 Å are due to airglow lines N I and He I in second order, respectively. We conclude that, unlike β Pic, 2 And shows no evidence of such chromospheric activity. Though much brighter in the visible (see Table 2), β Pic is more than 5 times fainter than 2 And in the far-ultraviolet. Unlike 2 And, the photospheric spectrum of β Pic is steadily rising toward the long-wavelength end of the *FUSE* region, showing no sign of Lyα absorption.

We also compared our *FUSE* spectrum of 2 And with another well-studied β Pic–like system: 51 Oph is a young A0 V (Houk & Smith-Moore 1988) or B9.5 IVe star (Slettebak 1982) with both circumstellar gas and circumstellar dust. The photospheric spectrum of 51 Oph is remarkably similar to 2 And (Fig. 5), and they have similar nonphotospheric absorption features (discussed in the next section). Circumstellar disks are more likely to be detected around stars with high $v \sin i$, such as β Pic (139 km s^{-1}),

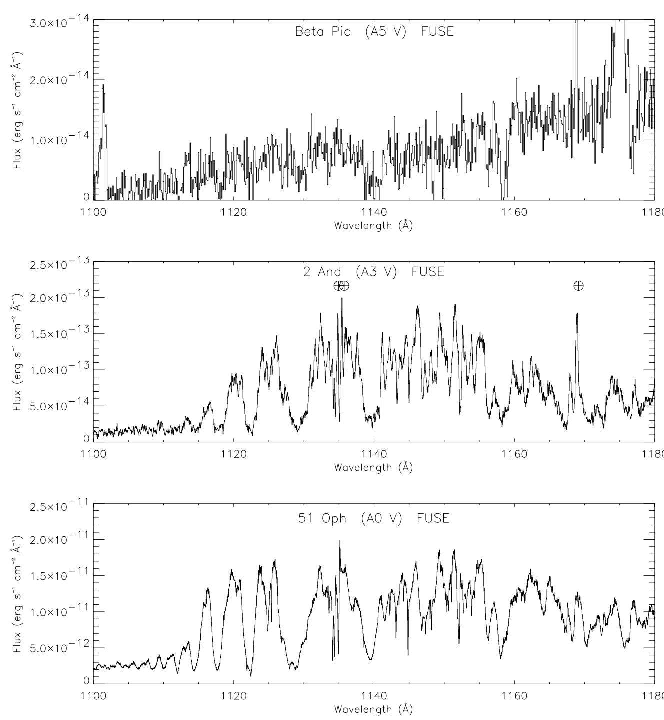

FIG. 5.—Comparison of *FUSE* spectrum of 2 And (*middle*) with *FUSE* spectra of β Pic (*top*) and 51 Oph (*bottom*). *Middle*, Airglow and geocoronal emission lines marked.

2 And (190 km s^{-1}), and 51 Oph (267 km s^{-1}; Dunkin, Barlow, & Ryan 1997). Using *FUSE*, Roberge et al. (2002) report β Pic–like circumstellar gas absorption in the 51 Oph circumstellar disk, including possible variability. They used the ionization fraction of nitrogen to derive a temperature of 20,000 to 34,000 K for the transient infalling material in 51 Oph. For 2 And there is not enough flux around 1080 Å to show the circumstellar N II lines.

3.4. *Circumstellar Gas Absorption Lines in 2 And's FUSE Spectrum*

Our *HST* GHRS observations of the Fe II UV line multiplet near 2600 Å (Cheng et al. 1997) suggest that the CS gas in the 2 And system must be between 3000 and 10,000 K. With this temperature range, we derived the circumstellar Fe II column density range of (4.79–4.93)$\times$ 10^{12} cm^{-2}. We further estimated a total H I column density range of (1.48–1.53)$\times$ 10^{17} cm^{-2}, which is much less than the CS gas column density for β Pic deduced by Hobbs et al. (1985) using Zn and Ca lines. The new *FUSE* spectrum of 2 And allows us to detect hotter circumstellar gas.

We found many narrow absorption lines in 2 And's *FUSE* spectrum. Some of these observed narrow absorption features are Fe III lines arising from hyperfine levels of the ground state. The Fe III resonance UV1 multiplet is an excellent diagnostic of circumstellar gas (Snow, Peters, & Mathieu 1979). Only one of these lines (1122.526 Å) has interstellar contamination. The predominant purely circumstellar Fe III lines in the 1120–1140 Å region are the Fe III triplet near 1131 Å (Fig. 6).

The detectability of these narrow absorption lines depends on several factors in addition to their equivalent width. Blended lines, lines on a steeply sloping continuum, and lines formed at the base of saturated photospheric absorption cores could be strong but difficult to measure. We used a multiple Gaussian–fitting procedure (ICUR; see Neff et al. 1989 for a complete description) to measure the properties of the circumstellar absorption lines. The continuum is fitted with a quadratic function, and up to five Gaussian lines can be fitted simultaneously. Line widths can be constrained (to the instrumental resolution, for example) to better deconvolve the effects of line blends. The main source of uncertainty in any line-fitting procedure is the definition of the continuum level. We used our photospheric model spectrum as a guide whenever possible (Fig. 6, *top*, for example). For each line, we derived a best-fit central wavelength and equivalent width based on our best assumption for the photospheric continuum. We then derived a conservative range of equivalent widths by performing a series of fits with higher and lower continuum estimates.

Table 3 lists spectroscopic parameters and our measurements of circumstellar lines of Fe II, Fe III, Cr III, and Mn III. With the exception of Fe II, the ionization potentials required to produce these lines (16.18, 16.50, and 15.64 eV, respectively) are too high to be formed by photoionization in the circumstellar environment of 2 And.

All Fe III lines listed in Table 3 are very strong, with very good velocity agreement (+14 $\pm$ 2 km s^{-1}). The weaker Cr III and Mn III have a larger scatter in their velocity, but they are still predominantly redshifted compared with 2 And.

We also detected circumstellar Fe II absorption lines at 1146.95, 1153.27, and 1154.4 Å (Fig. 7). The Fe II and Fe III features could arise at separate levels in the circumstellar material, where different temperatures and densities prevail. At 10^4 K in LTE, Fe III strongly dominates, whereas Fe II dominates below $\approx$6000 K. The temperature range over

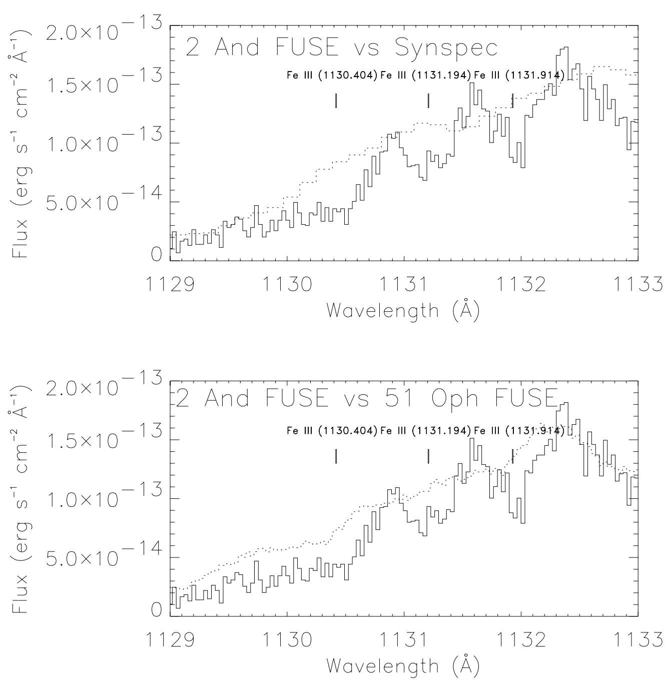

FIG. 6.—Purely circumstellar Fe III triplet near 1131 Å in 2 And (*solid line in each panel*) with synthetic spectrum (*top*, *dotted line*) and 51 Oph (*bottom*, *dotted line*).

TABLE 3

CIRCUMSTELLAR LINES IDENTIFIED IN THE *FUSE* SPECTRUM OF 2 AND

Lab Wavelength (Å)	E_{low} (cm^{-1})	$\lambda_{measured}$ (Å)	EW[a] (mÅ)	Velocity[b] (km s^{-1})
Fe II (7.87 eV):				
1146.952............	384.79	1146.899	200–240	−14
1153.272............	862.61	1153.362	180–240	+23
1154.399............	977.05	1154.312	180–225	−23
Fe III (16.18 eV):				
1124.883............	436.20	1124.932	25–50	+13
1126.728............	738.90	1126.791	25–40	+17
1130.404............	1027.30	1130.450	140–180	+12
1131.194............	932.40	1131.243	75–95	+13
1131.914............	738.90	1131.971	80–100	+15
Cr III (16.50 eV):				
1123.587............	27372.32	1123.585	15–25	−1
1125.736............	20703.64	1125.821	5–15	+23
1136.666............	25138.87	1136.766	5–20	+26
1138.797............	43304.53	1138.832	10–25	+9
Mn III (15.64 eV):				
1121.413............	32307.30	1121.410	15–40	−1
1124.109............	32307.30	1124.166	6–9	+15
1125.065............	32383.70	1125.087	30–40	+6
1127.093............	32368.90	1127.129	20–35	+10
1133.613............	51059.70	1133.747	20–40	+35
1136.867............	61580.20	1136.903	20–45	+10

[a] Range determined by multiple fits with different continuum placements.

[b] In rest frame of 2 And. Accuracy of the *FUSE* wavelength scale is $\pm$9 km s^{-1}.

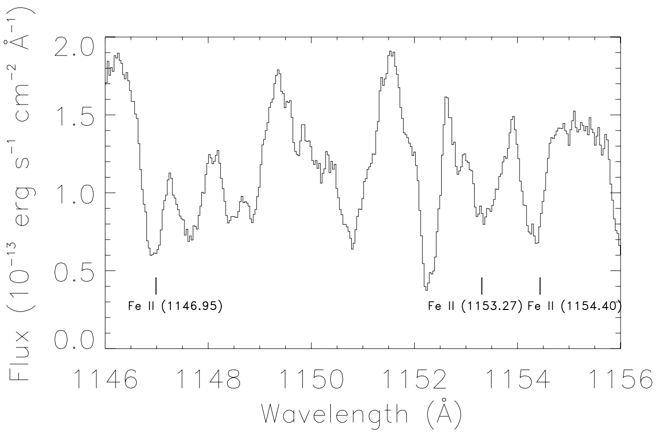

FIG. 7.—Circumstellar Fe II absorption lines clearly present in 2 And's *FUSE* spectrum.

which the two ions compete is very narrow (Snow et al. 1979).

Despite their similar ionization potentials, Cr III is likely formed in a higher density or lower temperature region than Fe III because of the large dielectronic recombination cross-section for Fe III (Snow et al. 1979). This further suggests that the circumstellar gas in the 2 And system might have regions with different temperature and density.

Roberge et al. (2002) detected the O I (^{1}D) absorption in the 51 Oph system. They claim that this line is purely circumstellar and that its presence implies temperatures around 23,000 K. In Figure 8 we show that a redshifted metastable O I (^{1}D) absorption line (1152.15 Å) feature is also present in 2 And's *FUSE* spectrum. For comparison, we obtained the processed *FUSE* data for 51 Oph and co-added the individual exposures to produce a high-resolution spectrum for 51 Oph. It was wavelength calibrated by achieving the best correlation with the photospheric lines (Fig. 8, *bottom*).

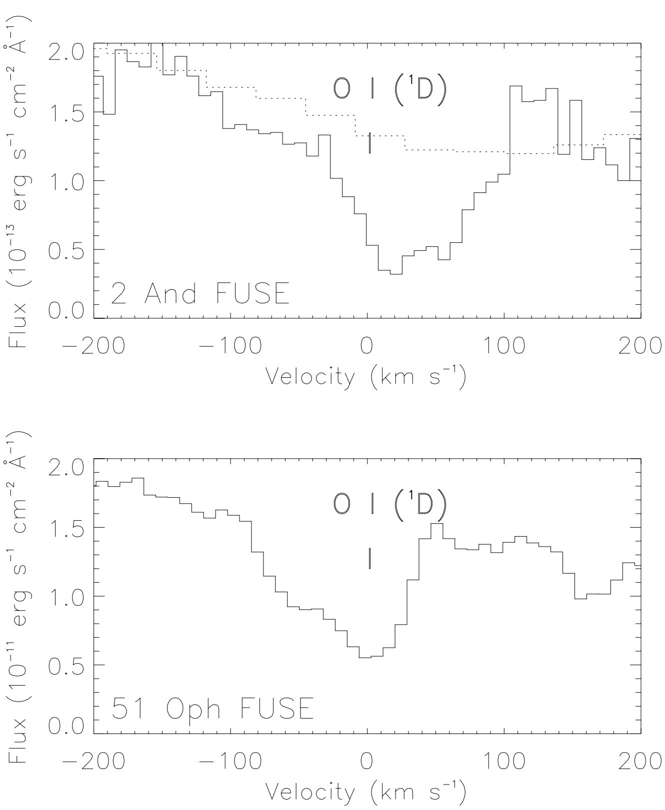

FIG. 8.—Purely circumstellar O I (^{1}D) absorption line arising from metastable state, appearing in the *FUSE* spectra of both 2 And and 51 Oph. *Top*, Fully calibrated *FUSE* spectrum of 2 And (*solid line*) and our photospheric model (*dotted line*) in the rest frame of 2 And ($v_{\rm rad} = +2$ km s^{-1}); *bottom*, *FUSE* spectrum for 51 Oph in its rest frame ($v_{\rm rad} = -12$ km s^{-1}).

4. SUMMARY AND CONCLUSIONS

Previous *Voyager* studies suggest that the FUV flux distribution for early A-type stars is very sensitive to $T_{\rm eff}$. In this study, we showed that the FUV spectrum (see Figs. 3 and 5) of 2 And (A3 V) is very similar to that of Vega (A0 V) and 51 Oph (A0 V or B9.5 IVe). This strongly suggests an earlier spectral type for 2 And. We derived a new effective temperature of 10,000 K for 2 And by simultaneously fitting a photospheric model to the observed UV (*IUE*) and FUV (*FUSE*) spectra.

2 And has many characteristics similar to the planetary system candidate β Pictoris. Visible and ultraviolet observations of both systems show variable redshifted absorption lines due to infalling circumstellar gas. However, unlike β Pictoris, 2 And's FUV spectra showed no evidence of chromospheric activity. Our single-epoch, relatively low spectral resolution (compared with our ground-based and *HST* GHRS studies) *FUSE* data do not permit us to better determine the origin of 2 And's infalling circumstellar gas.

The spectral range covered by *FUSE* contains many lines that are good diagnostics of circumstellar gas. The simultaneous presence of both Fe II and Fe III, along with lines of Cr III, Mn III, and the O I (^{1}D), suggests that the circumstellar gas in the 2 And system could include regions of different temperature and density. Given the absolute uncertainty in the *FUSE* wavelength scale, the measured redshift of the Fe III lines could be consistent with the variable +6 km s^{-1} Ca II K circumstellar feature observed in our ground-based studies.

We also compared the *FUSE* spectra of 2 And with another β Pic–like star, 51 Oph. Both systems show similar Fe II and Fe III lines in the 1120–1140 Å region. They also both show the metastable O I (^{1}D) line, which is formed at a higher temperature than that required to form both Fe II and Fe III. Although sublimation and subsequent photodissociation of water ice from comets might produce the O I (^{1}D) line seen in the *FUSE* spectrum of 51 Oph, it cannot explain the O I (^{1}D) line seen in the relatively "dust free" system 2 And.

To establish a general connection between circumstellar dust and gas, we need to study a larger sample of main-sequence A stars that have circumstellar gas, both with and without dust. To further study planetary system formation in these main-sequence A stars, we need to know their ages. A recent study suggests that β Pictoris might be as young as 12^{+8}_{-4} Myr (Zuckerman et al. 2001), but there is no published information regarding 2 And's age.

This work is based on observations made with the NASA-CNES-CSA *Far-Ultraviolet Spectroscopic Explorer*. *FUSE* is operated for NASA by Johns Hopkins University under NASA contract NAS 5-32985. Some of the data presented in this paper were obtained from the Multimission Archive at the Space Telescope Science Institute (MAST). Support for MAST for non-*HST* data is provided by the NASA Office of Space Science via grant NAG 5-7584 and by other grants and contracts. This research has made use the SIMBAD database, operated at CDS, Strasbourg, France. This research has been supported by NASA grant NAG 5-10312 and NSF grant AST 98-19737 to California State University, Fullerton, and NASA grant NAG 5-10313 to the College of Charleston.

REFERENCES

Andrillat, Y., Jaschek, C., & Jaschek, M. 1995, A&A, 299, 493
Baize, P., & Petit, M. 1989, A&AS, 77, 497
Beust, H., Vidal-Madjar, A., Ferlet, R., & Lagrange-Henri, A. M. 1990, A&A, 236, 202
———. 1994, Ap&SS, 212, 147
Bouret, J.-C., Deleuil, M., Lanz, T., Roberge, A., Lecavelier des Etangs, A., & Vidal-Madjar, A. 2002, A&A, 390, 1049
Chavez, M., Stalio, R., & Holberg, J. B. 1995, ApJ, 449, 280
Cheng, K.-P., Bruhweiler, F. C., Kondo, Y., & Grady, C. A. 1992, ApJ, 396, L83
Cheng, K.-P., Bruhweiler, F. C., & Neff, J. E. 1997, ApJ, 481, 866
Cheng, K.-P., Neff, J. E., & Bruhweiler, F. C. 1995, BAAS, 27, 861
Cowley, A., Cowley, C., Jaschek, M., & Jaschek, C. 1969, AJ, 74, 375
Deleuil, M., et al. 2001, ApJ, 557, L67
Dunkin, S. K., Barlow, M. J., & Ryan, S. G. 1997, MNRAS, 290, 165
ESA. 1997, The *Hipparcos* and Tycho Catalogues (ESA SP-1200) (Noordwijk: ESA)
Hauck, B., & Jaschek, C. 2000, A&A, 354, 157
Hobbs, L. M., Vidal-Madjar, A., Ferlet, R., Albert, C. E., & Gry, C. 1985, ApJ, 293, L29
Holweger, H., & Rentzsch-Holm, I. 1995, A&A, 303, 819
Houk, N., & Smith-Moore, M. 1988, Michigan Spectral Survey (Ann Arbor: Univ. Michigan), 4
Hubeny, I., Lanz, T., & Jeffery, C. S. 1994, Newsl. Analysis Astron. Spectra, No. 20, 30
King, J. R., & Patten, B. M. 1992, MNRAS, 256, 571
Moos, H. W., et al. 2000, ApJ, 538, L1
Morgan, W. W., Keenan, P. C., & Kellman, E. 1943, Atlas of Stellar Spectra (Chicago: Univ. Chicago Press)
Neff, J. E., Cheng, K.-P., & Meiring, J. D. 2003, in preparation
Neff, J. E., Walter, F. M., Rodonò, M., & Linsky, J. L. 1989, A&A, 215, 79
Parenago, P. P. 1958, SvA, 2, 151
Paunzen, E., Weiss, W. W., Heiter, U., & North, P. 1997, A&AS, 123, 93
Roberge, A., Feldman, P. D., Lecavelier des Etangs, A., Vidal-Madjar, A., Deleuil, M., Bouret, J.-C., Ferlet, R., & Moos, H. W. 2002, ApJ, 568, 343
Sasseen, T. P., Hurwitz, M., Dixon, W. V., & Airieau, S. 2002, ApJ, 566, 267
Savage, B. D., & Mathis, J. 1979, ARA&A, 17, 73
Slettebak, A. 1982, ApJS, 50, 55
Snow, T. P., Peters, G. J., & Mathieu, R. D. 1979, ApJS, 39, 359
Venn, K., & Lambert, D. L. 1990, ApJ, 363, 234
Zuckerman, B., Song, I., Bessell, M. S., & Webb, R. A. 2001, ApJ, 562, L87