A SEARCH FOR SODIUM ABSORPTION FROM COMETS AROUND HD 209458

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ABSTRACT

We monitored the planet-bearing solar-type star HD 209458 for sodium absorption in the region of the stellar Na I D1 line that would be indicative of cometary activity in the system. We observed the star using the Hobby-Eberly Telescope High Resolution Spectrograph with a high signal-to-noise ratio (S/N) and high spectral resolution for six nights over the course of 2 years, from 2001 July to 2003 July. From modeling we determine a 20% likelihood of a detection, based on a predicted number of comets similar to that of the solar system. We find that our analytical method is able to recover a signal and that our S/N is sufficient to detect this feature in the spectral regions on either side of the core of the D1 line, where it is most likely to appear. No significant absorption was detected for any of the nights based on a 3 σ detection limit. We derive upper limits on the column density of sodium of \( \lesssim 6 \times 10^9 \) cm\(^{-2}\) for a signal in the region around the line core and \( \lesssim 2 \times 10^{10} \) cm\(^{-2}\) for a signal in the core of the photospheric D1 line. These numbers are consistent with the sodium released in a single periodic comet in our own system, although a higher S/N may be necessary to uncover a signal in the core of the D1 line. Implications for cometary activity in the HD 209458 system are discussed.

Subject headings: comets: general — planetary systems: formation — stars: individual (HD 209458) — techniques: spectroscopic

1. INTRODUCTION

The Falling Evaporating Bodies (FEB) scenario (Lagrange et al. 1992) was introduced as an explanation for time-variable circumstellar absorption features observed in the spectral lines of the A-type star \( \beta \) Pic (Lagrange et al. 1986; Beust & Morbidelli 2000). Similar features have also been observed in other early-type main-sequence stars and some Herbig Ae/Be stars, which are considered \( \beta \) Pic precursors (Welsh et al. 1998; Grady et al. 1997; Grinin et al. 1996). According to the FEB hypothesis, solid bodies with sizes typical of solar system comets are evaporated within the vicinity of the star, producing absorption lines when observed along the line of sight (Ferlet, Hobbs, & Vidal-Madjar 1987; Lagrange-Henri, Vidal-Madjar, & Ferlet 1988). The high frequency of infalling comets is a phenomenon invoked in models of the early solar system and corresponds to the clearing-out stage in a system’s formation (Welsh et al. 1998; Beust et al. 1998). The mechanism behind the infall of these bodies is thought to be from the gravitational perturbation by at least one planet (Beust & Morbidelli 2000). Monitoring known planet-bearing solar analogs for comet activity would then give insight into the evolution of an exosolar system, and such a wide study would investigate how comet populations evolve in time and with stellar mass. In addition, searching for comet disks and clouds orbiting other stars offers a new method for inferring the presence of planetary systems (Stern 1995).

Sungrazing comets and periodic comets are quite frequent in our own system. Since the first light of the Solar and Heliospheric Observatory (SOHO) Large Angle and Spectrometric Coronograph (LASCO) on 1995 December 30, over 600 new sungrazing comets have been discovered (\(~60 \text{ yr}^{-1}\); see the SOHO Sungrazer Web site). In addition, the number of cataloged periodic comets totals \(~900\), with half having perihelia \( \lesssim 1 \) AU (Biswas 2000). Comets evaporate a significant amount of material as they approach perihelion in the form of a coma and tails. For example, Halley’s comet loses \(~0.001\) of its mass every perihelion passage (\(~10^{11} \) kg; Zellik & Gregory 1998). Hale-Bopp is a richer dust factory: in its 1997 appearance, it lost a total dust mass of \(~3 \times 10^{13} \) kg (Jewitt & Matthews 1999). The absorption features expected for many species known to be present in comets are quite weak because of the small column densities. Cremonese et al. (1997) discovered a sodium tail in comet Hale-Bopp (C/1995 O1), which is a third type of cometary tail consisting of neutral atoms. Sodium has also been observed in the tail of some other bright comets and in the comae of comets that were located at around 1 AU from the Sun (e.g., comet 1P/Halley; Wanatabe et al. 2003). Sodium is a good candidate for extrasolar detection because it is detectable even when the column density is low (Cremonese et al. 1997), and sodium has already been detected in absorption from gas in the \( \beta \) Pic disk (Hobbs, Albert, & Gry 1985), in variable absorption in some Herbig Ae/Be stars (Sorelli, Grinin, V. P., & Natta 1996), and in the atmosphere of the exosolar planet HD 209458b (Charbonneau et al. 2002).

HD 209458 is a solar-type star with a close-in Jovian-type planet. It is oriented edge-on to our line of sight, making it an ideal candidate for absorption spectroscopy and the detection of orbiting bodies. This has initiated several new exoplanet discoveries. It is the first exosolar system for which repeated transits across the stellar disk have been observed (Charbonneau et al. 2000). This allowed Charbonneau et al. (2002) to make the first observation of an exosolar planet atmosphere through the detection of neutral sodium absorption. More recently,
Vidal-Madjar et al. (2003) detected atomic hydrogen, which is associated with the upper atmosphere of the planet.

Here we observe HD 209458 for neutral sodium absorption from a comet crossing the line of sight. We present spectra of HD 209458 in the vicinity of the Na D1 line (5895.9243 Å). In § 2 we present the data and describe the data reduction technique. We analyze the data and remove the photospheric contribution of sodium. In § 3 we use our simulation of a cometary sodium absorption feature to examine its position in relation to the photospheric sodium line and its shape based on expected values of the column density, in order to define a search region. A synthetic spectrum is analyzed to check the reliability of our method. In § 4 we examine the residuals, discuss the results, and derive upper limits for the column density of sodium on each night. We use modeling to determine the likelihood of detecting a comet and conclude with possible explanations for the nondetection and a discussion of comet activity in the system.

2. OBSERVATIONS AND ANALYSIS

Observations of HD 209458 were made with the High Resolution Spectrograph (HRS) on the 9.2 m Hobby-Eberly Telescope (HET; Tull 1998). The HRS is a fiber-coupled echelle spectrograph, using an R-4 echelle mosaic with cross-dispersing gratings. The camera images onto a mosaic of two 2K × 4K CCDs with 15 μm pixels and a gap between them that spans ~72 pixels. The spectrograph was used in high-dispersion mode, with an average resolving power of $R = \lambda / \Delta \lambda \approx 115,000$ measured from thorium lines, corresponding to a resolution element of ~0.049 Å in the region of interest. The spectral coverage for the cross-dispersion setting used was between 4076 and 7838 Å. Observation dates and parameters are listed in Table 1. The star HD 12235 was also observed to serve as a reference system. We observed for two nights on 2002 August 28 and 31, using the same instrumental settings as for HD 209458. Stellar parameters are listed in Table 2.

Images typically had an integration time of 5–25 minutes depending on brightness and a total integration time between 1 and 2 hr. A Th-Ar lamp was observed before and after each sequence of exposures. Because of sodium emission lines in the flat-field illumination lamp, it was necessary to use extremely high signal-to-noise ratio (S/N) observations of rapidly rotating B and A stars as flat fields. These calibration stars were observed as near in time to the program stars as possible. The data were reduced using the publicly available IRAF software package. Continuum normalization was performed by selecting continuum regions in each image without obvious absorption lines or bad pixels and fitting a higher order polynomial to these sections. Images were then combined with appropriate rejection algorithms. Wavelength calibration of the spectra was obtained using the Th-Ar lamp comparison spectra for each data set. The 2002 December 9 data were missing a calibration star, so the lamp was used for flat-fielding, with the sodium emission lines removed using a polynomial fit to obtain a featureless spectrum. The S/N pixel$^{-1}$ in the continuum for each image is listed in Table 3. Figure 1 shows the reduced spectra for HD 209458 for each of the six nights. The spectra have been shifted to the rest frame of HD 209458.

The D1 line was used for analysis, since the D2 line is heavily contaminated by telluric lines (Ge 1998). The broad photospheric sodium line was removed using a polynomial fit (see Fig. 1), including multiple rejection iterations, and the normalized spectrum was searched for possible narrow absorption features up to 0.7 Å from the photospheric line center. Several absorption features above 3σ were attributed to telluric features that were removed imperfectly because of changes in observing conditions between exposures of HD 209458 and the calibration star. This is the case for the 2002 October 10 spectrum, where there is a significant absorption feature around 5896.5 Å; the feature is also present in the calibration star used for flat-fielding. On 2001 July 7, observing conditions were deteriorated by the fourth exposure,

| Star          | Observation Date | Heliocentric Velocity (km s$^{-1}$) | Number of Exposures | Time per Exposure (s) |
|---------------|-----------------|-------------------------------------|---------------------|-----------------------|
| HD 209458     | 2001 Jul 7      | 21.29                               | 4                   | 500                   |
|               | 2001 Jul 9      | 20.78                               | 2                   | 900                   |
|               | 2002 Oct 10     | −16.4                               | 2                   | 1500                  |
|               | 2002 Nov 23     | −26.36                              | 2                   | 1500                  |
|               | 2002 Dec 9      | −26.46                              | 2                   | 1500                  |
|               | 2003 Jul 14     | 19.60                               | 1                   | 3600                  |
| HD 12235      | 2002 Aug 28     | 23.60                               | 2                   | 1200                  |
|               | 2002 Aug 31     | 22.70                               | 3                   | 1000                  |

| Object        | Age (Gyr) | Spectral Type$^a$ | Radius$^b$ ($R_\odot$) | $T_{\text{eff}}^b$ (K) | $L^b$ ($L_\odot$) | $V^c$ (mag) | $V^a$ Radial Velocity (km s$^{-1}$) |
|---------------|-----------|-------------------|------------------------|----------------------|----------------|-------------|----------------------------------|
| HD 209458     | 5.2$^b$   | GO V              | 1.18                   | 6000                 | 1.61           | 7.7         | −14.8                            |
| HD 12235      | 5.39$^c$  | G2 IV             | . . .                  | . . .                | . . .          | 5.9         | −17.4                            |

$^a$ SIMBAD data retrieval system (of the Astronomical Data Center in Strasbourg, France).

$^b$ Cody & Sasselov 2002.

$^c$ Ibukiyama & Arimoto 2002.
which is the cause of the absorption feature near 5895.86 Å. No absorption features greater than 3 σ due to cometary activity were identified.

3. MODELING

Simulations were run to produce estimates of the position and shape of a sodium absorption feature due to solar-like comets in the HD 209458 system. Constraints on spatial and chemical characteristics of cometary bodies were taken from observations of short- and long-period comets in our own system, mainly the comets Halley and Hale-Bopp (Krishna Swamy 1997; Zeilik & Gregory 1998; Cremonese et al. 1997). Although sungrazing comets also display tail and coma features, they are much smaller than periodic comets, only a few kilometers to hundreds of kilometers in diameter.

The position of the feature depends on the velocity of the comet when detected; as a comet moves within ∼3 AU, the cometary nucleus begins to display coma formation followed by the extension of gas and ion tails. Full display of the comet tail occurs between 1.0 and 1.5 AU (Biswas 2000), with sodium extending beyond 10^5 km from the nucleus (Oppenheimer 1980). In Hale-Bopp the length of the sodium tail was measured to be 3 × 10^7 km (Cremonese et al. 1997). In order to obtain the maximum column density along the line of sight, a theoretical comet velocity was calculated specifically for an orientation aligned with the sodium tail, which points roughly antistarward, and an orbit that lies in the plane of the ecliptic, which for HD 209458 is oriented edge-on to our line of sight. Since the radius and luminosity of HD 209458 are larger than for the Sun, the orbital distance for an orientation aligned with the sodium tail, which lies in the plane of the HRS. The equivalent width of a sodium absorption line with a column density of 10^10 cm^-2 is ∼1 mÅ.

3.1. Synthetic Detection: Check on the Analysis

As a check of our analytical method we input our synthetic absorption features into the observed spectrum and recover the absorption through fitting the broad stellar sodium D1 line profile. We use the data from 2002 November 23, since telluric features have been successfully removed and the S/N is the highest. (The features were not removed in 2002 December 9 data.) Since the detection limit is lower in the continuum than in the core of the line, we place the feature in the continuum (S/N = 237) with a column density of 6.4 × 10^9 cm^-2 and in the core (S/N = 88) with a column density of 1.7 × 10^10 cm^-2, derived in § 4.1 as the 3 σ upper limits for this date. We also place a feature in the wing of the line with a column density of 9.3 × 10^9 cm^-2 based on a calculated S/N

| Observation Date | S/N in Continuum | S(\text{Na} i) Upper Limit (cm^-2) | S/N in Line Core | S(\text{Na} i) Upper Limit (cm^-2) |
|------------------|------------------|-----------------------------------|------------------|-----------------------------------|
| 2001 Jul 7........| 70               | 2.2 × 10^10                       | 23               | 6.5 × 10^10                       |
| 2001 Jul 9........| 110              | 1.4 × 10^10                       | 36               | 4.3 × 10^10                       |
| 2002 Oct 10.......| 198              | 7.6 × 10^9                        | 67               | 2.3 × 10^10                       |
| 2002 Nov 23........| 237              | 6.4 × 10^9                        | 88               | 1.7 × 10^10                       |
| 2002 Dec 9.........| 258              | 5.8 × 10^9                        | 88               | 1.7 × 10^10                       |
| 2003 Jul 14........| 204              | 7.4 × 10^9                        | 67               | 2.2 × 10^10                       |

| Observation Date | S/N in Continuum | S(\text{Na} i) Upper Limit (cm^-2) | S/N in Line Core | S(\text{Na} i) Upper Limit (cm^-2) |
|------------------|------------------|-----------------------------------|------------------|-----------------------------------|
| 2001 Jul 7........| 70               | 2.2 × 10^10                       | 23               | 6.5 × 10^10                       |
| 2001 Jul 9........| 110              | 1.4 × 10^10                       | 36               | 4.3 × 10^10                       |
| 2002 Oct 10.......| 198              | 7.6 × 10^9                        | 67               | 2.3 × 10^10                       |
| 2002 Nov 23........| 237              | 6.4 × 10^9                        | 88               | 1.7 × 10^10                       |
| 2002 Dec 9.........| 258              | 5.8 × 10^9                        | 88               | 1.7 × 10^10                       |
| 2003 Jul 14........| 204              | 7.4 × 10^9                        | 67               | 2.2 × 10^10                       |

The range of velocity shifts for a spectral feature have been calculated using the parameters of the short-period (SP) comet Halley (e = 0.967, a = 18 AU, P = 76 yr, and perihelion distance q = 0.587 AU) and the long-period (LP) comet Hale-Bopp (e = 0.9951, a = 187 AU, P = 2550 yr, and q = 0.914 AU). Figure 2 shows the wavelength and corresponding Doppler shift for both types of comet. The velocity and thus the wavelength shift for Halley peaks at 1.17 AU, with a maximum shift of 0.53 Å from the photospheric line center. For Hale-Bopp the maximum velocity is reached at 1.83 AU, which results in a maximum wavelength shift of 0.43 Å. The majority of the orbit, from ∼1 to 3 AU, for both types of comet will produce a wavelength shift of ∼0.4 Å. Since the D1 line is ∼0.6 Å wide, a feature will most likely be in the wing or continuum region. We also take into consideration the periodic comets with perihelia less than those of Halley and Hale-Bopp (∼220 comets; Biswas 2000), which would produce a greater wavelength shift. Our search for Na absorption will be within ±0.7 Å of the stellar Na D1 line.

The depth and shape of the feature depend on the column density and temperature of the absorbing material. A model of the signal was created using a Voigt absorption profile, which was then convolved with the instrumental spectral resolution. Figure 3 shows model absorption lines based on the core and continuum upper limits derived for our best S/N data, from 2002 December 9, in § 4.1. Estimates of the column density of sodium from evaporating comets in other systems are on the order of 10^10 cm^-2 from HR 10 (FEB; Welsh et al. 1998) and from β Pic (disk; Hobbs et al. 1985). The thermal broadening can be calculated by assuming a gas temperature for the comet coma and tail. The estimated temperature for the sodium tail of a comet, from solar system observations, is 150 K (Krishna Swamy 1997), and atomic parameters for the sodium D1 line were taken from Morton (1991). The inherent Doppler width at 150 K corresponds to only 0.03 Å, and therefore a single radial velocity absorption component would be spectrally unresolved, with the instrumental FWHM of 0.049 Å of the HRS. The equivalent width of a sodium absorption line with a column density of 10^10 cm^-2 is ∼1 mÅ.
of 162. The feature was added at the stage just before the removal of the photospheric D1 line. Our method of polynomial fitting was able to recover the features at the core, wing, and also continuum region. The residuals and recovered absorption features are shown in Figure 4. The equivalent width of the recovered features are $1.6 \pm 0.6$, $1.0 \pm 0.3$, and $0.62 \pm 0.2$ mA, for the core, wing, and continuum, respectively. These are all consistent with the input values of $1.7$, $0.9$, and $0.6$ mA, for the core, wing, and continuum, respectively. This demonstrates proof that the stellar D1 line profile fitting technique can recover narrow sodium features from comet events.

4. RESULTS AND DISCUSSION

4.1. Upper Limits on Sodium Column Density by Comets

The residuals after the photospheric sodium line is removed are shown in Figure 5. No signal was detected in any of the spectra, but upper limits were determined based on a $3 \sigma$ detection limit. The $1 \sigma$ upper limit to the equivalent width for the undetected feature was determined by

$$W_e = \int \frac{F_c - F_d}{F_c} \, d\lambda \approx \Delta \lambda \sigma,$$

Fig. 1.—HD 209458 on all six nights and HD 12235. The fit to the D1 line is overplotted with a dashed line. The spectra have been shifted to the rest frame of the system.
where $F_c$ is the normalized flux in the continuum, $F_k$ is the normalized absorption line, $\Delta \lambda$ is the spectral resolution element of 0.049 Å, $N_c$ is the number of counts in the continuum, gain = 0.6320 e$^-$/ADU$^-$, $\epsilon$ is the read noise 2.70 e$^-$, and $p$ is the pixel number in the cross-slit direction used for sampling a spectrum. It is appropriate to assume that the absorption line is in the linear portion of the curve of growth, where the column density is proportional to the equivalent width. The integrated number of sodium atoms per square centimeter in the line of sight is then given by

$$N = \frac{mc^2}{\pi e^2 f} \int_0^\infty \frac{F_c(v) - F_k(v)}{F_k(v)} dv = 1.130 \times 10^{20} \frac{W_j \lambda^2}{f} \text{ cm}^{-2},$$

where $f$ is the oscillator strength ($f = 0.318$ for 5895.9243 Å; Morton 1991) and $W_j$ and $\lambda$ are in units of angstroms. The upper limits for each date are given in Table 3. In the continuum region, the column density for each night ranges from $\sim 6 \times 10^9$ to $2 \times 10^{10}$ cm$^{-2}$, whereas in the region of the D1 line the core upper limits range from $\sim 2 \times 10^{10}$ to $7 \times 10^{10}$ cm$^{-2}$. This appears to be consistent with the solar comet sodium column density [e.g., sodium absorption from an occultation of the solar system comet Giacobini-Zinner resulted in upper limits of $N(\text{Na} i) < 2 \times 10^{11}$ cm$^{-2}$, based on solar abundance ratios for K $i$; Schempp & Hayden Smith 1989]. For comparison, we also show the residual for the reference star HD 12235 in Figure 6. This star was reduced in exactly the same manner as for HD 209458, and the stellar sodium D1 line was fitted and removed using the same methods as for HD 209458. As expected, no features were present in the spectra on either night. The 3 $\sigma$ upper limits are $1.1 \times 10^{10}$ cm$^{-2}$ (2002 August 28) and $9.4 \times 10^9$ cm$^{-2}$ (2002 August 31), which are in agreement with our results for HD 209458.

### 4.2. Detection Probability

Since no signal was detected we examine the likelihood of observing a comet crossing based on the amount of time the comet spends within an observable window. We only consider the orbit within 3 AU, since comet features will not be significant beyond this distance from the star. The amount of time the comet spends in front of the star is determined by the...
diameter of the star, \( D_{\text{sun}} \), and the tangential velocity, \( v_{\text{tan}} \). This time will vary depending on the orientation of the orbit to our line of sight. The radius of HD 209458 is \( 1.18 \, R_{\odot} \approx 8.21 \times 10^8 \) km, which is comparable to the width of the sodium tail, \( 8 \times 10^8 \) km (see the NASA Hale-Bopp Web site). For the total time in front of the star within a year for any comet in the system, we multiply by the average number of periodic comets per year, \( \sim 25 \), of which are SP comets (Halley type) and \( \sim 15 \) of which are LP comets (Hale-Bopp type; Krishna Swamy 1997). We double this, since our observations are over the course of 2 years. The time that any SP comet spends in front of the star over 2 years ranges between 7 and 35 days for \( v_{\text{tan}} \) varying from 11 to 54 km s\(^{-1}\), with an average time in front of the star of 10 days. For LP comets the time ranges between 13 and 42 days for \( v_{\text{tan}} \) varying from 14 to 44 km s\(^{-1}\), with an average time of 18 days in front of the star. Since our observing time is small compared to the time comets spend in front of the star and observing a comet can be considered a random process, the probability can be efficiently described by a Poisson distribution \( P(t, \tau) = 1 - e^{-\mu} \), where \( e^{-\mu} \) is the probability of observing zero events over the total combined observing window and \( \mu = \tau N \) is the average number of events for the combined observations. The value \( \tau \) is defined as the average number of comets observable at any time, which can be calculated by multiplying the total amount of time that a single comet would spend in the line of sight by the estimated number of comets per year and then dividing by the total time (1 yr); \( N \) is the total number of chances to see a comet, defined as the total number of observing sessions. An observing session is defined as the period of time needed to reach the S/N necessary to detect sodium absorption. This calculation assumes that the observable windows for the different comets do not overlap, a reasonable assumption considering the estimated number of comets and amount of time each one spends in front of the star. Since the estimated number of comets per year can be considered to be constant over our monitoring period, the chances of observing a comet are insensitive to the elapsed time between observations and depend only on the average number of comets per year in the system and the total number of observing sessions.

The probability as a function of the number of observing sessions for our LP and SP cometary models are plotted in Figure 7. The probability of detecting either type of periodic comet from six observations (in 2 years, 2001–2003) ranges from 16% to 55%, with an average probability of 20%. According to these probabilities, then, we would need to make \( \sim 20 \) observations to achieve a 50% likelihood of observing a comet. As a more conservative estimate we consider only the scenario in which we are looking directly into the sodium tail, which would maximize the column density. This then decreases \( D_{\text{sun}} \) to essentially the stellar radius and gives a probability of about half the values listed above, and we would need to make double the amount of observations to be certain of a 50% chance. The probability could also vary depending on the number of comets in the system. In Figure 8 we show how the number of comets affects the probability using the average, minimum, and maximum time a comet spends in front of the star and our current number of observations. There would need to be \( \sim 150 \) total comets yr\(^{-1}\) for us to have a 50% chance with our current number of observations.

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4 The NASA Goddard Space Flight Center Hale-Bopp Web site is available at http://www.gsc.nasa.gov/ftp/pub/pao/releases/1997/97-40.htm.
This implies that it would be necessary to either continue with more observations of this system or expand our target list to cover many more systems in order to have a better chance of detecting a comet event.

4.3. Theoretical Column Density

For comparison, we have also conducted theoretical calculations on the column density we would expect from typical comet events. Using measurements of comet Hale-Bopp we calculate an approximate column density of sodium in the tail. Using the production rate and lifetime of neutral sodium atoms listed in Cremonese et al. (1997) of $Q(\text{Na}) \approx 5 \times 10^{25}$ atoms s$^{-1}$ and $\tau = 1.69 \times 10^5$ s$^{-1}$ at 1 AU (which for Hale-Bopp is very close to perihelion, $q = 0.914$), we estimate the column density of the tail to be $4 \times 10^9$ cm$^{-2}$. Soon after the discovery by Cremonese et al. (1997) of the sodium tail, Wilson, Mendillo, & Baumgardner (1998) discovered that there was a second sodium tail (termed the diffuse sodium tail) superposed on the dust tail with a production rate of sodium very similar to that determined for the pure sodium tail. If we consider the sodium in both sodium tails and the contribution of sodium in the coma [which was estimated to be $Q(\text{Na}) \approx 1 \times 10^{23}$ atoms s$^{-1}$ by Combi, Disanti, & Fink 1997], the total production rate increases to $1 \times 10^{26}$ atoms s$^{-1}$, and the column density increases to $\sim 8 \times 10^9$ cm$^{-2}$. Combi et al. (1997) argue that, based on solar abundances and the production...
rate of oxygen \(10^{30} \text{ cm}^{-2}\), the total production rate of sodium should be a few times \(10^{27} \text{ cm}^{-2}\), which would lead to a column density of \(\sim 8 \times 10^{9} \text{ cm}^{-2}\). Based on our upper limits, we would be able to detect a feature of this column density if it were offset from the rest wavelength of the star. This is likely, since from Figure 2 it is shown that the majority of the orbit will produce at least a 0.4 Å shift. The upper limits determined in § 4.1 are on the order of the column density of sodium from a single periodic comet, which verifies that we would be able to detect the passage of a single comet. With the probability, this suggests an upper limit of \(\sim 300\) total comets yr\(^{-1}\) that come within 3 AU of HD 209458 (based on a 95% probability [2 \(\sigma\)]). Considering that the \(\beta\) Pic system has \(\sim 300\)–1000 FEBS yr\(^{-1}\) (Lagrange et al. 1992; Ferlet et al. 1993), this upper limit is consistent with a more evolved system.

5. CONCLUSION

We monitored the planet-bearing solar-type star HD 209458 for comet activity using the HET over the course of 2 years with six observations with S/N values between 70 and 258. Our observations of the sodium D1 line were examined for variable absorption components, as seen in \(\beta\) Pic and other stars, which are considered to be signatures of this type of activity. From modeling, we determined that a feature with a detectable column density of \(\sim 10^{10} \text{ cm}^{-2}\) would have a FWHM of \(\sim 0.05\) Å and a \(W_p\) of \(\sim 1\) mÅ and could be shifted up to \(\sim 0.5\) Å from the photospheric line center. Simulations based on typical solar system periodic comets showed that the probability of a detection from six observations was \(\sim 20\%\) and was insensitive to the total elapsed time between observations. The probabilities derived suggest that less than \(\sim 300\) total comets yr\(^{-1}\) come within 3 AU of HD 209458, or one would have likely been detected. No absorption features greater than 3 \(\sigma\) due to cometary activity were identified.

Our upper limits for the sodium column density for each observation are consistent with the column density expected from the sodium tail of solar-type comets. Some possible reasons for the nondetection are as follows:

1. There were a small number of observations. This system is expected to have comet activity on a scale similar to the solar system, since it is a \(\sim 5\) Gyr old solar-type star (Cody & Sasselov 2002). With only six observations in 2 years, our chances of witnessing a comet crossing were quite small. We plan to continue to monitor this star with many more observations.

2. A comet was passing, but it was not detectable to us. The inclination of the comet’s orbit might have been such that it was not within our line of sight. However, in the solar system, 87% of short-period comets have inclinations within 30°, and

![Fig. 6.—Reference star HD 12235. Residual from the polynomial fit to the photospheric D1 line. The dashed line represents 3 \(\sigma\).](image_url)

![Fig. 7.—Maximum (dashed line), average (solid line), and minimum (dot-dashed line) probabilities of detection. Left: SP comets. Right: LP comets.](image_url)
81% have perihelia latitudes less than 10° from the ecliptic (all of them are within 30°; Biswas 2000). Long-period comet inclinations are more scattered about the ecliptic, with only 47% having inclinations less than 90° and 63% having perihelia latitudes less than 30° (Biswas 2000). Thus, inclination may factor into the probability when considering long-period comets.

3. The sodium feature was at the rest wavelength of the star. This would occur if the comet was detected at perihelion, which would be a less likely circumstance for periodic comets, since they spend only a small fraction of their time there. If it were the case, however, based on estimates of the column density of the sodium tail from a single comet, our S/N in the core of the D1 line might not be sufficient to uncover a signal. For our future observations we plan to obtain higher S/N data.

Continued monitoring of HD 209458 will occur over the next year, and observations are planned for several other planet-bearing stars. Through continued observations we can improve our upper limits for the number of comets in the planetary system around HD 209458 and increase our chances of detecting a cometary event.

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