SEARCH FOR H_3^+ IN HD 141569A[1,2]

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ABSTRACT

A search for H_3^+ line emission, reported to have been detected toward the young star HD 141569A and possibly originating in a clump of planet-forming gas orbiting the star, has yielded negative results. Observations made at the United Kingdom Infrared Telescope and the Subaru Telescope during 2001–2005 covered 11 major transitions of H_3^+ from 3.42 to 3.99 μm. No H_3^+ emission lines were detected; one marginal detection at 3.9855 μm in 2002 June was not confirmed in later spectra. The upper limits to the line strengths were significantly lower than the previously reported detections. Supplemental slit-scanning spectroscopy using adaptive optics was performed within 0″.38 of HD 141569A to search for extended emission from H_3^+, but no emission was detected. We compare our upper limit to the luminosity in H_3^+ from HD 141569A with that possible from a gas giant protoplanet and also from a jovian mass exoplanet in close orbit about its central star.

Subject headings: circumstellar matter — ISM: lines and bands — ISM: molecules — planetary systems: protoplanetary disks — stars: individual (HD 141569A)

Online material: color figures

1. INTRODUCTION

The detection of the $Q(1, 0)$ and $Q(3, 0)$ emission lines of vibrationally excited H_3^+ near 4.0 μm was recently reported by Brittain & Rettig (2002, hereafter BR02) toward the nearby star HD 141569A. Apart from a highly tentative detection of H_3^+ in SN 1987A (Miller et al. 1992), this is the first claim of H_3^+ *in emission* from beyond the solar system. HD 141569A is a young star with a debris disk that has been extensively observed in the visible to mid-infrared region (Augereau et al. 1999; Weinberger et al. 1999; Fisher et al. 2000; Mouillet et al. 2001; Marsh et al. 2002; Brittain et al. 2003; Clampin et al. 2003). The H i lines in emission in the visible part of the spectrum indicate high chromospheric activity (Andrillat et al. 1990). The small infrared excess ($L_{IR}/L_* = 8 \times 10^{-3}$; Sylvester & Skinner 1996) of the object is comparable to other debris disk objects ($L_{IR}/L_* = 10^{-3}$ to 10^{-4}), implying that the dust in HD 141569A is dissipating and already mostly removed (Malfait et al. 1998). The low abundance of circumstellar CO (Zuckerman et al. 1995) also suggests that HD 141569A is approaching the zero-age main sequence and is currently in transition from a Herbig Ae/Be star to a gas-exhausted Vega-type object. Weinberger et al. (2000) used spectroscopy of the low-mass companions of HD 141569A to constrain the age of the system to 5 ± 3 Myr, between those of Herbig Ae/Be stars

and the archetypical Vega-type star β Pic ($\sim$20 Myr; Barrado y Navascués et al. 1999). The time interval of 1–10 Myr after star formation is critical for planet formation, since the building of Jupiter-like planets is believed to take place during that period (e.g., Lissauer 1993; Pollack et al. 1996). Observations of HD 141569A and other transition objects are needed to understand if, when, and how gas giant planets form around the intermediate-mass stars.

Although interstellar H_3^+ has been detected in absorption for almost a decade (Geballe & Oka 1996; McCall et al. 1998, 1999, 2002; Geballe et al. 1999; Goto et al. 2002; Brittain et al. 2004), the molecular ion has never been definitively found in emission except in the planetary atmospheres of our solar system. The most prominent H_3^+ emission in the solar system is the aurora at the Jovian poles (Drossart et al. 1989; Oka & Geballe 1990). Miller et al. (2000) discussed the feasibility of detecting H_3^+ in giant exoplanets brought into close orbits around their stars and concluded that detection would be difficult.

The H_3^+ line intensities reported by BR02 are remarkably high compared to those of Jupiter. From the equivalent width of the $Q(3, 0)$ line, the peak of which BR02 observed to be roughly 5% above the continuum of HD 141569A, and the distance of 99 pc to HD 141569A (van den Ancker et al. 1998), the total luminosity of that line alone is $\sim$3 $\times 10^{19}$ W. In comparison, the total H_3^+ luminosity from Jupiter (Miller et al. 2000) is $\sim10'$ times less. This huge disparity demonstrates that the putative line emission from HD 141569A cannot arise in a giant planet. BR02 suggested that the line-emitting H_3^+ may be distributed in a huge gas giant protoplanet with a volume of $\sim$1 AU^3 or at the inner edge of the circumstellar disk at a distance no less than 17 AU from the star, but they did not identify physical mechanisms that might lead to the production of the required amount of vibrationally excited H_3^+.

The goals of the observations reported here were to confirm the presence of H_3^+ in HD 141569A and obtain better diagnostics of the physical state of the circumstellar gas of HD 141569A by examining a wide range of H_3^+ and possibly other transitions in the 3–4 μm region. In the following sections we describe our

[1] Based on data collected at the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

[2] Based on data collected at the United Kingdom Infrared Telescope, which is operated by the Joint Astronomy Centre on behalf of the UK Particle Physics and Astronomy Research Council.

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TABLE 1
Observing Log

UT Date	Line	Telescope	Instrument	Resolution	Slit Width (arcsec)	Slit P.A. (deg)	Integration[a] (minutes)	Atmospheric Standard
2001 Sep 30..........	$R(1, 1)^u$, $R(1, 0)$	UKIRT	CGS4	$R = 33,000$	0.45	90	24	HR 5892 (A2 Vm)
2002 Jun 21	Multiple lines[b]	Subaru	IRCS	$R = 20,000$	0.15	0	96	HR 6194 (A3 IV)
2002 Jun 21	Multiple lines	Subaru	IRCS	$R = 20,000$	0.15	90	96	HR 6194
2003 May 20.........	Multiple lines	Subaru	IRCS+AO	$R = 20,000$	0.15	0	24	HR 5685 (B8 V)
2003 May 20.........	Multiple lines	Subaru	IRCS+AO	$R = 20,000$	0.15	0	60[c]	HR 5685
2005 Mar 2–4.......	$Q(3, 0)$	UKIRT	CGS4	$R = 21,000$	0.8	90	285	HR 5511 (A0 V)

[a] On-source integration time.
[b] Includes $R(3, 3)^u$, $R(4,4)^l$, $R(1, 1)^u$, $R(1, 0)$, $R(1, 1)^l$, $Q(2, 2)$, $Q(1, 1)$, $Q(1, 0)$, $Q(2, 1)^l$, $Q(3, 0)$, and $Q(3, 1)^l$.
[c] Sum of slit scans across $\pm 0\rlap{.}''38$ at HD 141569A, except for the exposures at the position of the star.

observations and data reduction, report the results, and compare them with H_3^+ line intensities that might be expected in a variety of situations.

2. OBSERVATIONS

Initial observations of HD 141569A were made at the United Kingdom Infrared Telescope (UKIRT) on 2001 September 30 using the facility $1-5 \mu$m spectrometer CGS4 (Mountain et al. 1990). More comprehensive searches were made at the Subaru Telescope on 2002 June 21 and 2003 May 20 with the facility's Infrared Camera and Spectrograph (IRCS; Tokunaga et al. 1998; Kobayashi et al. 2000). An additional measurement using UKIRT was made in 2005 March. An observing log is provided in Table 1.

The UKIRT observations in 2001 utilized CGS4's echelle to cover the region of the H_3^+ $R(1, 1)^u R(1, 0)$ ortho-para doublet at 3.67 μm, with the $0\rlap{.}''45$ wide slit of the spectrograph oriented east-west. The resolving power of the instrument in this mode was 33,000. The measurements and the data reduction were performed in a manner similar to those reported by Geballe & Oka (1996) and Geballe et al. (1999). The spectrum of HR 5892, observed prior to and after HD 141569A, was used to remove telluric absorption lines and provided wavelength calibration accurate to 8×10^{-6} μm rms.

At Subaru, the echelle and a cross-dispersing grating in the IRCS were employed to cover one-third of the wavelength range from 3.22 to 4.01 μm. The grating angles were set to record the following major H_3^+ transitions in one exposure: $R(3, 3)^u$, $R(4, 4)^l$, $R(1, 1)^u$, $R(1, 0)$, $R(1, 1)^l$, $Q(2, 2)$, $Q(1, 1)$, $Q(1, 0)$, $Q(2, 1)^l$, $Q(3, 0)$, and $Q(3, 1)^l$, which includes the two lines reported by BR02. The narrow slit ($0\rlap{.}''15 \times 5\rlap{.}''6$) was used to obtain spectra with a resolving power of $R = 20,000$. The slit position angle was set to $0°$ and $90°$ in the first run in 2002 June (Fig. 1). The telescope was nodded $2\rlap{.}''8$ along the slit to allow subtraction of the sky emission and the dark current. The on-source integration time for each slit angle was 96 minutes. An early-type star HR 6149 (A0 V) was observed immediately after
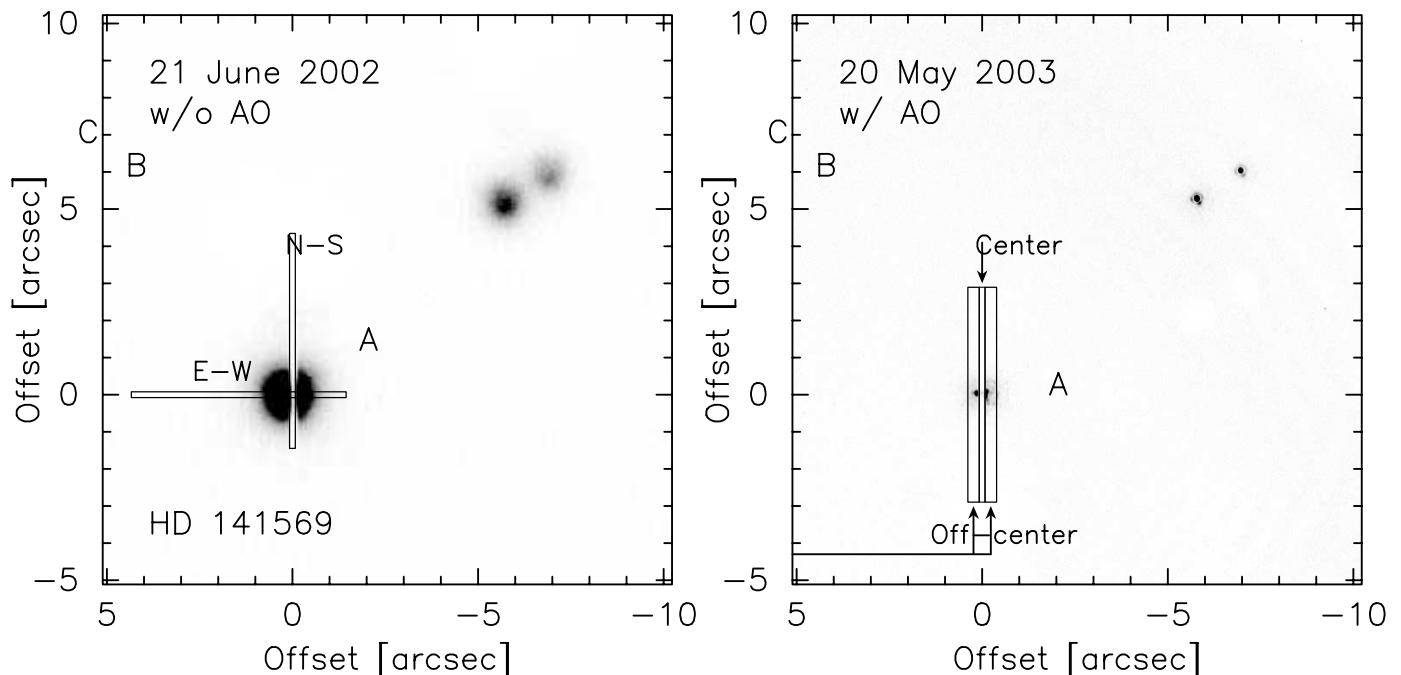

Fig. 1.—Slit positions at Subaru overlaid with the images obtained by the slit viewing camera. HD 141569 is a triple system consisting of primary HD 141569A with faint companions B and C at $8\rlap{.}''6$ northwest (Weinberger et al. 2000). *Left*: K-band image on 2002 June 21 under natural seeing conditions. *Right*: L'-band image on 2003 May 20 obtained with the AO system. Offsets were performed as shown to search for H_3^+ line emission detached from the central star.
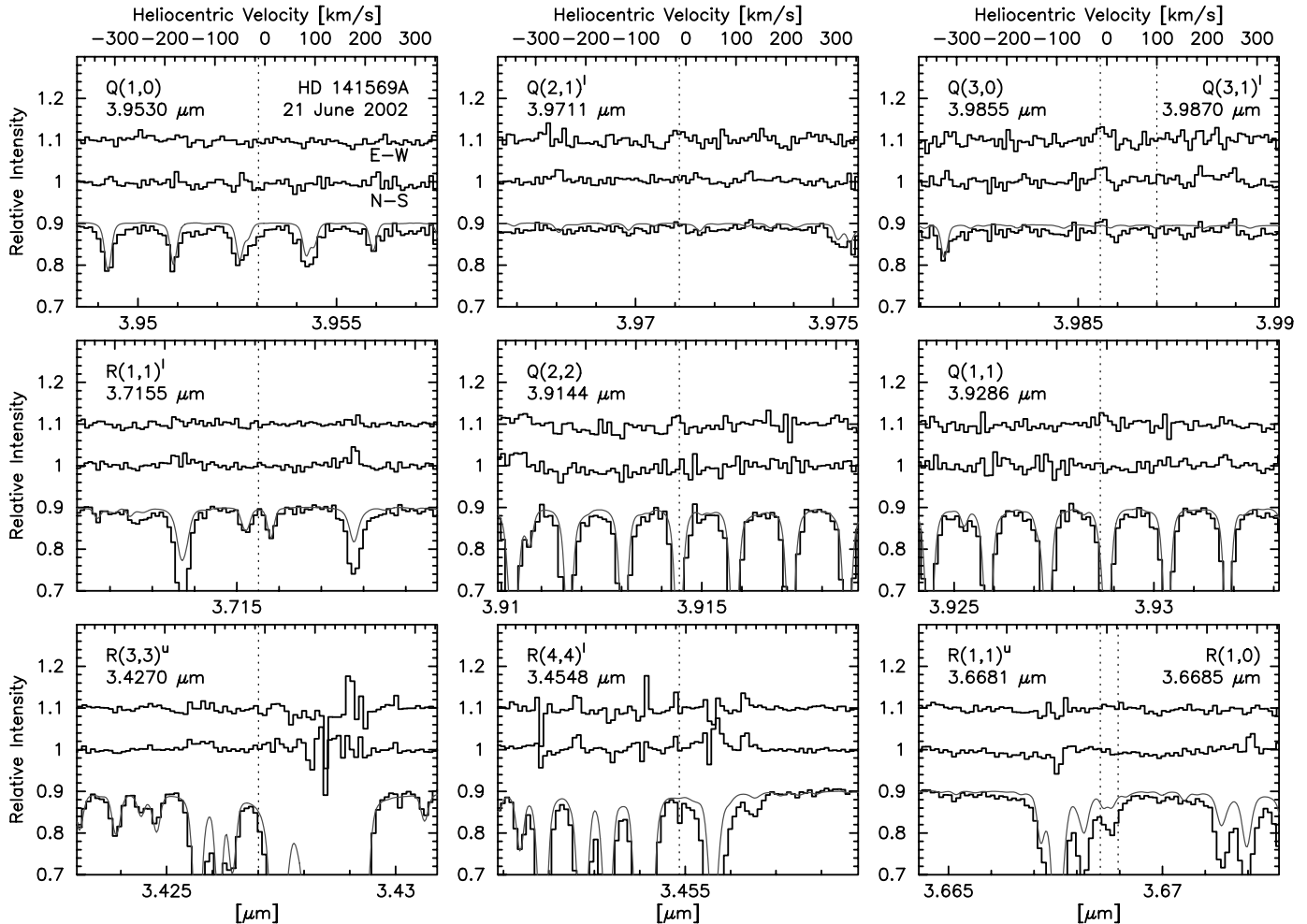
F_IG. 2.—Subaru spectra of HD 141569A on 2002 June 21. Spectral segments at each H$_3^+$ transition are shown in individual panels. The upper spectrum in each panel was recorded with the slit aligned east-west, while the middle spectrum was recorded with the slit aligned north-south (Fig. 1). The bottom trace represents the north-south spectrum before ratioing with the standard star spectrum. The overlay shows the atmospheric transmission curve calculated by ATRAN (Lord 1992). Spectra are vertically offset by ±0.1. Dotted lines are at expected positions of H$_3^+$ lines (Lindsay & McCall 2001) and include corrections for a heliocentric velocity of −13 km s^{-1} (BR02) and the Earth's orbital motion. [*See the electronic edition of the Journal for a color version of this figure.*]

HD 141569A as a spectroscopic standard. A spectroscopic flat field was obtained at the end of the night using a halogen lamp that is in the calibration unit at the telescope's cassegrain port in front of the entrance of the spectrograph.

The second Subaru observing run was carried out in the same manner but with the facility adaptive optics (AO) system (Gaessler et al. 2002; Takami et al. 2004), a 36 element curvature-base system that delivers nearly diffraction-limited images at wavelengths longer than 2 μm. The AO system improved the transmission through the slit by 2–4 times over the seeing-limited condition. The slit position angle was aligned north-to-south, along the apparent major axis of the circumstellar disk. A two-point dithering sequence was provided by a tip-tilt mirror inside the AO system. The on-source integration time was 24 minutes. Supplemental slit-scanning spectroscopy was performed over an area 0″.38 on each side of HD 141569A, which is ±38 AU in projection at the distance of the object. The telescope was moved to blank sky 10″ north of HD 141569A in between the exposures at each slit position. HR 5685 (B8 V) was observed as an atmospheric standard star at air mass similar to the program star. The spectroscopic flat field was obtained during the night immediately after HD 141569A, without moving the telescope or the instrument rotator, in order to minimize the fringes in the spectrum.

CGS4 was used at UKIRT during 2005 March 2–4 to search for the Q(3, 0) line of H$_3^+$ at 3.985 μm, with HR 5511 as the telluric standard. Because of poor seeing conditions, a somewhat wider slit (0″.85) was employed than in 2001, producing a resolving power of 21,000.

3. REDUCTION OF SUBARU DATA

Consecutive frames recorded in the dithering sequence at Subaru were subtracted to remove the sky emission, and the subtracted frames were stacked together. For slit-scanning spectroscopy blank sky echellograms were subtracted. The pixel-by-pixel variation of the detector response was normalized by ratioing with dark-subtracted flat field images. Outlier pixels were determined based on the statistics of the dark current and flat field images. The signals in these pixels were determined by interpolation before extracting one-dimensional spectra. All the above procedures were handled with IRAF[10] packages for image reduction and aperture extraction.
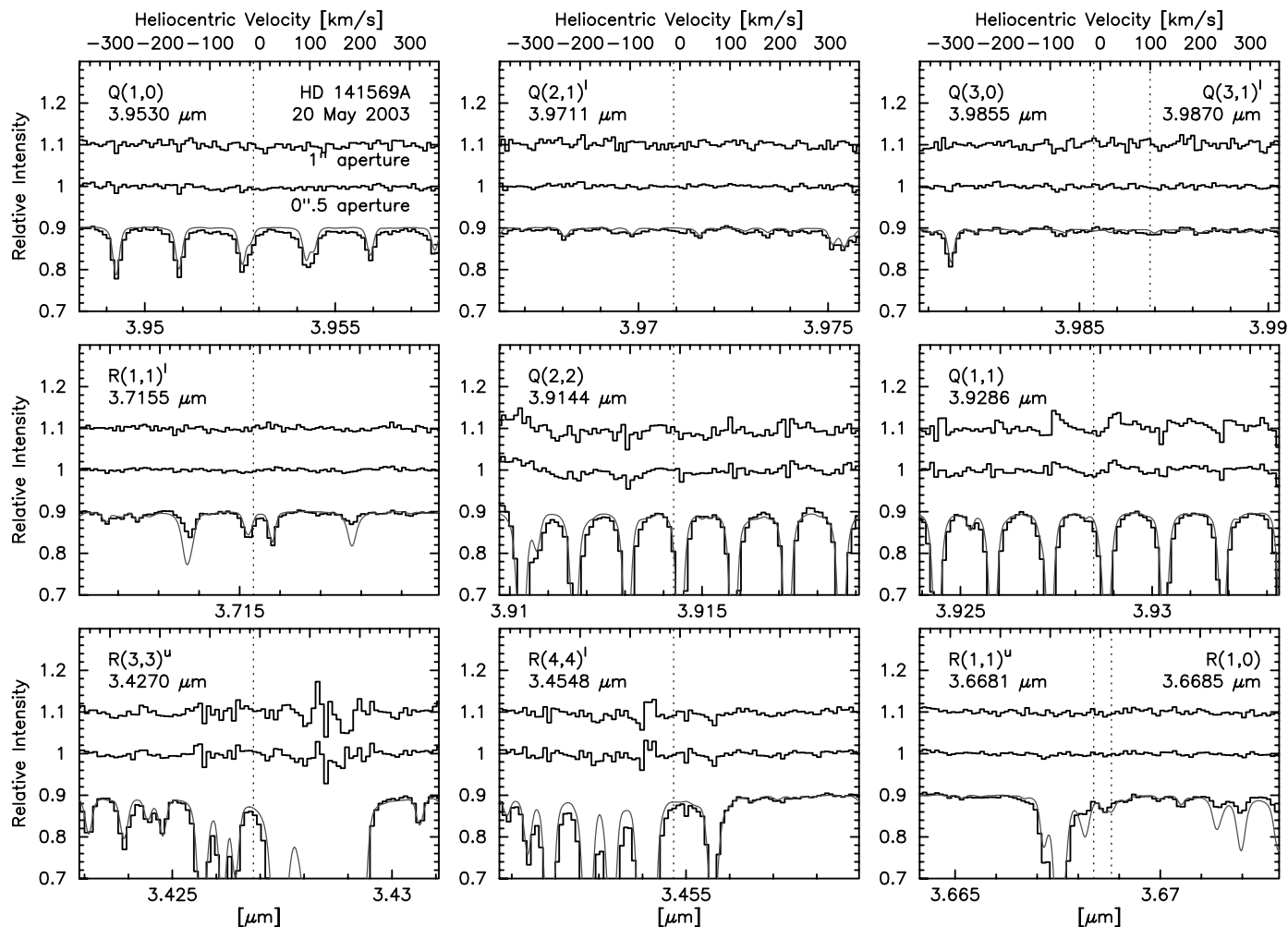
FIG. 3.—Same as Fig. 2, but for the second run on 2003 May 20 with an AO system. Upper trace is extracted from a 1″0 aperture; middle trace is from 0″5 aperture. The bottom trace represents the spectrum with 0″5 aperture before ratioing with the standard star spectrum. [*See the electronic edition of the Journal for a color version of this figure.*]

Wavelength calibration was performed by maximizing the cross-correlation of the observed spectra with the atmospheric transmission curve modeled by ATRAN (Lord 1992). The uncertainty of the wavelength calibration is dependent on the local line density but is typically better than a tenth of a pixel $<1 \times 10^{-5}$ μm (0.75 km s^{-1}). Further processing included linear registration of the standard star and object spectra, rescaling of the standard star spectrum according to Beer's law to minimize the mismatch of the air mass, convolving the spectrum to equalize the slightly different spectral resolutions, and finally dividing by the standard star spectrum to eliminate the atmospheric absorption lines. Some of the fully processed data showed periodic wavy features with amplitude smaller than 2% of the continuum flux. This fringing pattern was removed by discarding a few protruding frequencies in the Fourier-transformed spectra.

The reduced Subaru spectra from 2002 June and 2003 May are shown in Figures 2 and 3, respectively. Both the north-south and east-west slit spectra are shown in Figure 2; in Figure 3 spectra extracted from 0″5 and 1″0 apertures along the slit are shown. The slit-scanning spectra obtained in the second run are shown in Figure 4. The data from off-center regions to the east and the west of HD 141569A were summed in order to provide a higher signal-to-noise ratio.

4. RESULTS

No emission lines were detected at the wavelengths of any of the H$_3^+$ transitions covered by these observations. In fact, no emission lines whatsoever were detected at any of the wavelengths covered. Limits for unresolved and marginally resolved lines are typically a few percent of the continuum.

The sensitivity of each of the Subaru observations was estimated using the standard deviation of the fluctuations in the continuum. The statistics were obtained over the data points shown in each panel in Figures 2 and 3. The detection limits per resolution element (2 pixels) for the emission lines are 4%–5% (3 σ) for the first run in 2002 June, and $\sim$2% for the second run in 2003 May, except for those few transitions having severe overlap with strong telluric absorption lines. The 3 σ noise levels in the UKIRT spectra are $\sim$4% of the continuum per resolution element (3 pixels) near the ortho-para doublet (except on the strong telluric CH$_4$ complex at 3.6675 μm) and $\sim$0.8% of the continuum per resolution element (2 pixels) near the $Q(3, 0)$ line.

The two Q-branch lines in the spectrum reported by BR02 are strong enough that they would have been seen clearly in the Subaru and UKIRT spectra, which were obtained at similar resolutions as those obtained by BR02. In addition to this, the
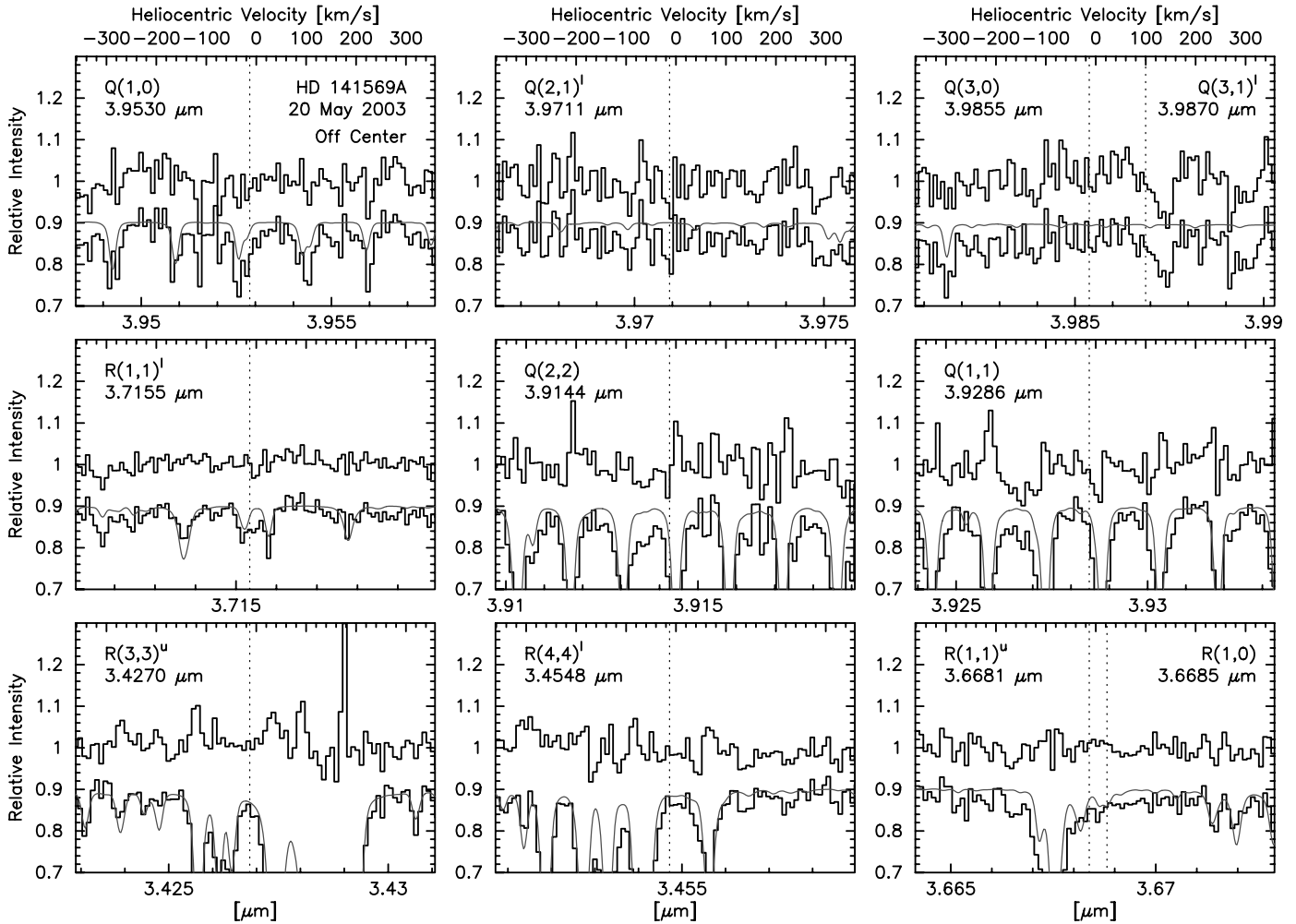
Fig. 4.—Same as Fig. 2, but for the slit-scanning spectroscopy conducted during the second run. The signals in the off-center region $\pm 0\rlap{.}''38$ in the east and the west of HD 141569A are summed in the upper traces; the lower traces are the unratioed spectra. The continuum is due to spillover from the central star and is roughly a quarter of that in Fig. 3. [*See the electronic edition of the Journal for a color version of this figure.*]

absences of many of the other emission lines, in particular the $R(1, 1)^u R(1, 0)$ ortho-para doublet at 3.67 μm, which was not detected either at Subaru or at UKIRT (Fig. 5, *upper panel*), nor by BR02, are difficult to reconcile with the reported detections of the $Q(1, 0)$ and $Q(3, 0)$ lines. In Jupiter all of those lines are observed with comparable intensities (Maillard et al. 1990). The $Q(1, 0)$ and $Q(3, 0)$ lines originate in $(J, G) = (1, 0)$ and $(3, 0)$ levels of the vibrationally excited state, respectively. The accidental doublet, consisting of the $R(1, 0)$ and $R(1, 1)^u$ transitions, arises from the $(J, G) = (2, 0)$ and $(2, 1)$ levels in the $\nu = 1$ state. All known plasma sources of H$_3^+$ produce fairly thermal distributions of population, with the exception of an enhancement of metastable levels in very low density media (Oka & Epp 2004). We are not aware of a physical mechanism that could explain the emission from the vibrationally excited $(1, 0)$ and/or $(3, 0)$ states without causing emission from the excited $(2, 0)$ state.

There is a modest bump near the wavelength of the $Q(3, 0)$ line in the 2002 June Subaru spectrum, which is marginally above the noise level and roughly half the strength of the line reported by BR02. A possible identification of the bump could be C I at 3.98546 μm (2509.12 cm^{-1}), which is shifted by only -1.7 km s^{-1} from the vacuum wavelength of $Q(3, 0)$. However, the feature is not detected in the 2003 May data in a spectrum with 2 times higher signal-to-noise ratio. The UKIRT spectrum
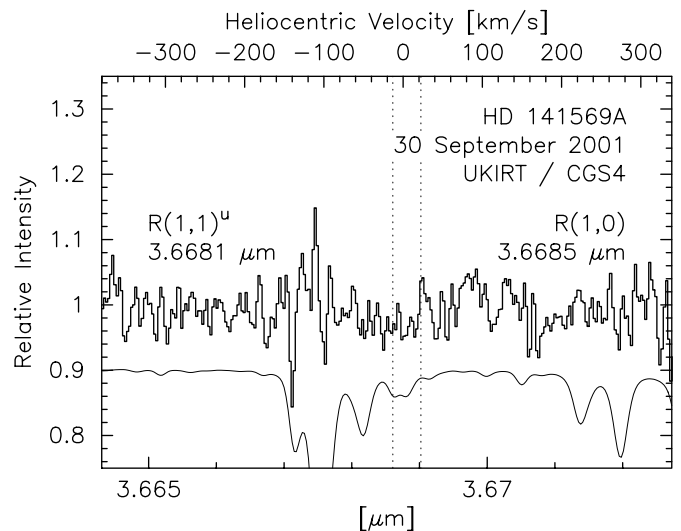

Fig. 5.—$R = 33{,}000$ spectrum of HD 141569A at the $R(1, 1)^u$ and $R(1, 0)$ doublet observed on 2001 September 30 at UKIRT. The expected line positions of the doublet at the time of observing are marked with dotted vertical lines.
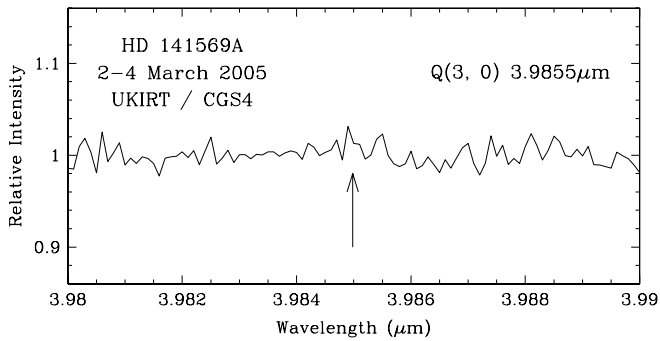
Fig. 6.—$R = 21,000$ spectrum of HD 141569A at the $Q(3, 0)$ line observed on 2005 March 1–3 at UKIRT. The expected line position is marked with an arrow.

at the $Q(3, 0)$ line from 2005 March (Fig. 6) could be interpreted as containing a weak and broad emission whose center is near the expected wavelength of the line. However, no narrow line with strength approaching that reported by BR02 is present.

The Subaru spectra at the $Q(1, 0)$ and $Q(3, 0)$ lines are more closely compared with those of BR02 in Figure 7 in order to examine the possible role of interference from telluric lines. In this figure the raw Subaru spectra are presented, prior to correction for atmospheric absorption, in order to make a direct comparison with Figure 2 of BR02, in which telluric absorption features are not removed. On 2001 August 9, the line identified as $Q(1, 0)$ by BR02 was found at 3.95318 μm, redshifted by 47 km s^{-1} from a strong absorption line of N_2O (3.95256 μm), and by 31 km s^{-1} from a weaker line of CH_4 (3.95277 μm). The redshift of this line from the N_2O and CH_4 lines would have been 18 and 3 km s^{-1}, respectively, on 2003 May 20. It is possible that H_3^+ $Q(1, 0)$ emission is partially blocked by these lines, but neither of the lines is opaque. The overlap would have been less severe on 2002 June 21, with shifts of 34 km s^{-1} to

N_2O and 18 km s^{-1} to CH_4. Although the intensity of the emission line could be weaker than that observed by BR02, we believe $Q(1, 0)$ should have been detectable at least at the shoulder of CH_4 with the present spectral resolution. Overlapping telluric absorption lines do not explain the absence of $Q(3, 0)$, which is in a clean region, let alone other transitions, most of which are only modestly affected by atmospheric absorption lines.

One must also consider the possibility that the H_3^+ line emission could either be extended or localized at an off-center location of the star and detected only in the wider (1″) slit used by BR02. However, both the UKIRT 2001 September and Subaru 2002 June observations utilized the natural seeing and thus sampled the circumstellar material more or less evenly, without detecting line emission. The 2003 May Subaru observation was assisted by adaptive optics that achieved near–diffraction-limited image quality (point spread function 0″1 FWHM at 3.9 μm). Contamination of the central star spectrum by detached H_3^+ emission would have been minimal. The spectra obtained from wide aperture (1″) centered on the star show no significant difference except somewhat increased noise levels (Fig. 3). From that spectrum we can only rule out significant H_3^+ line emission due north or south of the central star in 2003. However, at that time we also undertook five-position slit-scanning spectroscopy within 0″38 of the central star, scanning from east to west (Fig. 1). The data were combined except at the position of the central star (Fig. 4). If asymmetric off-center line emission from H_3^+ contaminates the central star by as much as 10% of the continuum level as reported for the $Q(1, 0)$ line by BR02, the offset emitting spot should be very bright and readily detected. However, no line emission was seen, and the spectrum is dominated by a residual flat continuum from the central star. Thus, asymmetrically distributed H_3^+ line emission cannot be the cause of the discrepant results.

To summarize, we did not detect either of the two lines originally reported by BR02, at levels significantly lower than
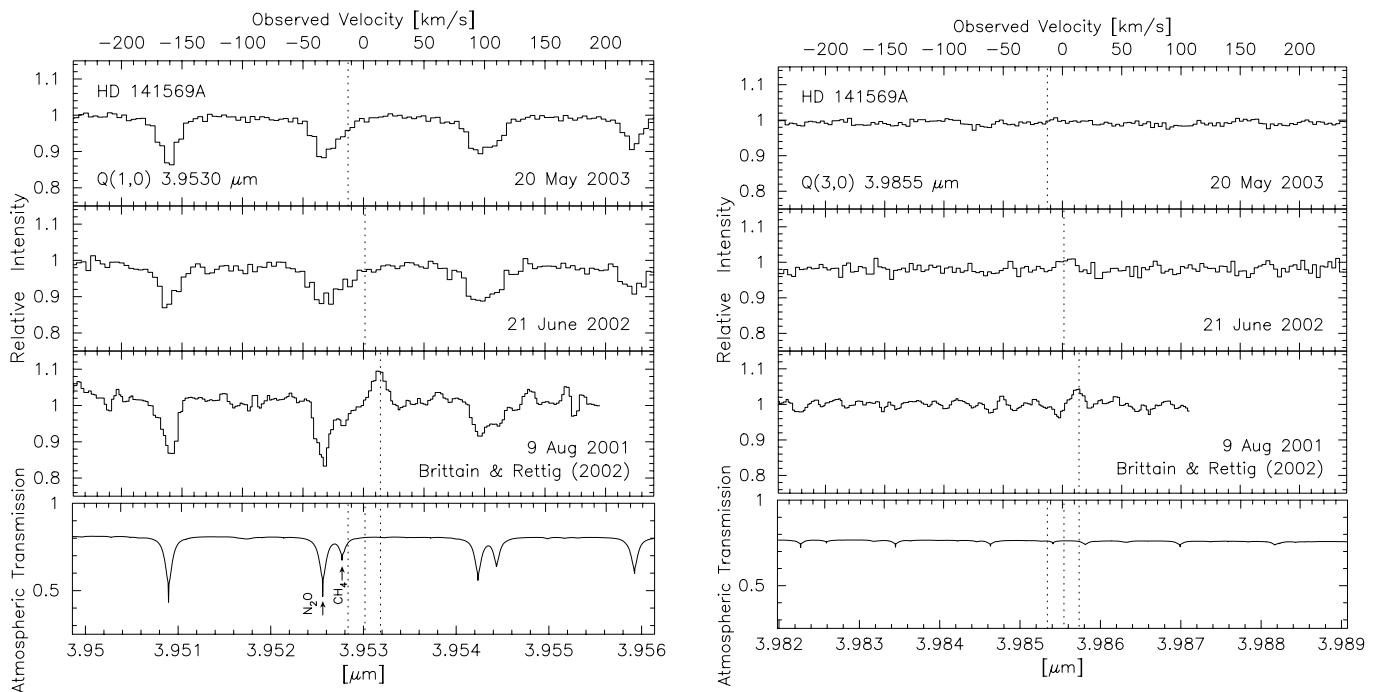

Fig. 7.—Detailed raw spectra of HD 141569A at the wavelengths of the H_3^+ $Q(1, 0)$ and $Q(3, 0)$, together with the spectra of BR02. The north-south and east-west Subaru spectra obtained in 2002 June have been summed. Dotted vertical lines denote the wavelengths that the $Q(1, 0)$ and $Q(3, 0)$ would appear in 2003 May and 2002 June. The bottom panels show the atmospheric transmission curves computed using ATRAN (Lord 1992). The identifications of the absorbing molecules were made with HITRAN database (Rothman et al. 2003).

they reported. T. Rettig (2004, private communication) continues to detect a line at the wavelength of the $Q(3, 0)$ line of H$_3^+$ with the Keck telescope at close to the originally reported strength. The discrepancy with our data is currently unresolved.

5. DISCUSSION

The most stringent 3 σ upper limits to the fluxes of H$_3^+$ emission lines searched for here, $\sim3\times10^{-19}$ W m^{-2}, correspond to upper limits of $\sim3\times10^{19}$ W to luminosities in these lines. These limits are more than 8 orders of magnitude greater than those from Jupiter's brightest lines. Thus, H$_3^+$ line emission from a Jupiter-like exoplanet in a Jupiter-like orbit is not likely to be detectable in the near future.

Brittain et al. (2003) detected emission lines near 5 μm from CO in HD 141569. The emitting CO is in a range of vibrational states, which they argued are excited by UV photons at the inner edge of the 17 AU disk. The H$_3^+$ lines reported by BR02 are approximately an order of magnitude weaker than the strongest CO lines. In dense clouds, where H$_3^+$ is created following collisional ionization of H$_2$ by cosmic rays, $n(H_3^+) \sim 1\times10^{-4}$ cm^{-3} (Geballe 2000) is many orders of magnitude less than $n(CO)$. One would expect line emission from vibrationally excited H$_3^+$ to be weaker than that from vibrationally excited CO, roughly by the ratio of their abundances, and therefore the H$_3^+$ lines to be undetectable. In principle, ionization of H$_2$ by UV photons could augment the abundance of H$_3^+$. However, that requires photons of energy at least 15.3 eV, higher than those that ionize atomic hydrogen. Such photons would be shielded from all but the extreme inner edge of the disk. Thus, whatever process produces the lines of excited CO from the circumstellar disk should not produce detectable H$_3^+$ line emission.

BR02 hypothesized that their reported H$_3^+$ line emission could arise in a gas giant protoplanet. We consider the conditions required for such emission, at the upper limit we observed, which corresponds to 6×10^{38} photons s^{-1} in a single line. We assume, as did BR02, that the emission is from a gaseous sphere of mass 5 times that of Jupiter that is 7 AU from HD 141569A. We assume a diameter of 1 AU for such an object (60% of the diameter of a Hill sphere, assuming a 3 $M_\odot$ star, appropriate for the spectral type of HD 141569A). The mean number density of such an object is $\sim10^{15}$ cm^{-3}. Assuming that interstellar conditions pertain for the creation and destruction of H$_3^+$, [$n(H_3^+) \sim 10^{-4}$ cm^{-3}; Geballe 2000], the sphere contains $\sim2\times10^{35}$ H$_3^+$ ions. The vibrational excitation mechanism for the H$_3^+$ is unknown but, as discussed above, cannot be absorption by UV photons. Here we consider the possibility of collisional excitation. If, for example, the temperature of the sphere is 600 K, the H$_3^+$ would be vibrationally pumped by collisions at a rate of $\sim4\times10^3$ s^{-1} (the rate coefficient is $\sim2\times10^{-9}$ cm^3 s^{-1} and the efficiency of vibrational pumping is $e^{-E/kT} \sim 2\times10^{-3}$) and would emit with an efficiency of $\sim6\times10^{-5}$ (the ratio of spontaneous emission to collisional relaxation) so that the photon emission rate, spread over a few tens of rovibrational lines, is $\sim1\times10^{35}$ s^{-1}. This is roughly 5 orders of magnitude below our observed upper limit. Thus, even at this probably unrealistically high temperature, one would need to invoke an H$_3^+$ production rate $\sim10^5$ times higher than the interstellar value, or alternatively severe depletions of *all* atomic and molecular species with which H$_3^+$ can easily react in order to reduce the overall reaction rate by $\sim10^5$. At lower temperatures the pumping rate by collisions would drop steeply, and an alternate excitation mechanism would be required.

Is the observational limit derived here a useful constraint on jovian exoplanets in much closer proximity to their central stars than the putative protoplanet of BR02 is to HD 141569A, or Jupiter is to the Sun? Miller et al. (2000) estimated that a gas giant planet of jovian mass at a distance of 0.05 AU, such as the τ Boo exoplanet, would have 3 orders of magnitude higher column density of H$_3^+$ in its ionosphere due to radiative ionization of H$_2$ followed by the rapid reaction of H$_2^+$ and H$_2$. One must also add ionization by the vastly denser stellar wind (10^4 times denser than at the distance of Jupiter). Countering the increased sources of H$_3^+$ will be sinks such as dissociative recombination of H$_3^+$ on electrons. Moreover, in the extreme environment in which the exoplanet's atmosphere is located, it is likely that a large fraction of the hydrogen will be atomic and thus unable to readily form H$_3^+$.

Miller et al. (2000) estimated that H$_3^+$ line fluxes emitted from the τ Boo ($d = 19$ pc) exoplanet could be a few times 10^{-21} W m^{-2}, a value 2 orders of magnitude lower than our upper limit but nominally less than an order of magnitude lower when the difference in distance is included. However, their estimate did not take into account the effects mentioned above that would significantly reduce the H$_3^+$ abundance. Moreover, the 25 times brighter continuum flux density of τ Boo than HD 141569A makes detection of a line of even this strength considerably more difficult there. Thus, we expect that the limit on H$_3^+$ luminosity reported here is several orders of magnitude above meaningful upper limits for even the most extreme gas giant exoplanet environments. It is possible that a giant protoplanet, perhaps somewhat more distant that 0.05 AU such that a significant fraction of its hydrogen is molecular, could glow more brightly in H$_3^+$ than a close exoplanet, but it is unlikely that any such object is currently in the solar neighborhood. In summary, we believe that detection of H$_3^+$ line emission from either type of object remains a formidable technical challenge.

6. CONCLUSION

We have searched unsuccessfully for line emission from H$_3^+$ in HD 141569A, obtaining upper limits significantly below the signal strengths reported by BR02, for both the lines that they reported to have detected and additional H$_3^+$ lines that one would expect would be of comparable strength. We also do not see any other lines in our data, which cover one-third of the 3.2–4.0 μm interval. Apart from a combination of time variability and a highly unusual and unknown excitation mechanism, we can find no viable explanation for the conflict between our results and those of BR02. We have found no plausible mechanism to produce, in either a gas giant protoplanet or in an exoplanet, H$_3^+$ luminosities approaching those reported by BR02 or our upper limits.

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