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FURTHER CONSTRAINTS ON THE PRESENCE OF A DEBRIS DISK IN THE MULTIPLANET SYSTEM GLIESE 876

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ABSTRACT

Using both the Very Large Array (VLA) at 7 mm wavelength, and the Australia Telescope Compact Array (ATCA) at 3 mm, we have searched for microwave emission from cool dust in the extrasolar planetary system Gliese 876 (Gl 876). Having detected no emission above our 3σ detection threshold of 135 μJy, we rule out any dust disk with either a mass greater than 0.0006 $M_\oplus$ or less than $\sim$250 AU across. This result improves on previous detection aperture thresholds by an order of magnitude, and it has some implications for the dynamical modeling of the system. It also is consistent with the Greaves et al. hypothesis that relates the presence of a debris disk to close-in planets. Due to the dust-planetesimal relationship, our null result may also provide a constraint on the population or composition of the dust and small bodies around this nearby M dwarf.

Key words: circumstellar matter – Kuiper Belt – planetary systems – planets and satellites: general – stars: individual (Gl 876)

1. INTRODUCTION

The M4 dwarf star Gl 876 harbors one of the nearest multiplanet systems detected to date. At a *Hipparcos*-determined distance of 4.69 pc (Perryman et al. 1997), this star is orbited by three planets (Delfosse et al. 1998; Marcy et al. 1998; Marcy et al. 2001). The outer two planets are gas giants, while the innermost is likely to be of terrestrial mass (Rivera et al. 2005). The semi-major axes of these planets range from 0.02 to 0.2 AU. We first targeted Gl 876 to detect any optical transits as described in Shankland et al. (2006).

The search for and study of planetary systems and dust disks around M dwarfs is a relatively new endeavor and the results to date have not been entirely consistent. Only a few debris disks are known around M stars, and Gautier et al. (2007) found no new detections in a *Spitzer Space Telescope* search for dust disks around 123 late-type dwarfs. However, the nearby M dwarf AU Mic shows a well-resolved debris disk, whose radius is between 50 and 210 AU (Kalas et al. 2004). In addition, Gl 842.2 (Lestrade et al. 2006) was shown to have a $\sim$300 AU disk, and Gl 182 (Liu et al. 2004) was found to have a $\sim$120 AU one. These suggest that Gl 876 could reveal a disk if it had one.

A disk detection is important in that it would offer a better understanding of the Gl 876 system, and it would begin to provide clues about planet formation around M dwarfs. M dwarfs comprise three-fourths of the galactic population, making any detection important to understanding plant formation for this most common type. A detection would also help to characterize a particularly diverse and nearby planetary system. Separate from the potential to witness disk disturbances which might reveal planets, a disk detection would further determine whether mature dust disks signal the presence of planets in a system, and help constrain whether debris disks are the ubiquitous result of planetary formation. Conversely, detecting *no disk* would still be helpful as it would set the system's upper mass limit.

Right now the inclination in Gl 876 is not well understood, and assessing any such "tilt" would help indicate whether the inclination approaches $i \approx 50°$, or is more like $i \approx 90°$. The former is contended as a result of radial-velocity reductions, as discussed in Rivera et al. (2005) and Shankland et al. (2006). The latter is derived using astrometric data from *Hubble Space Telescope*'s (*HST*) Fine Guidance Sensor (FGS) by Benedict et al. (2002). Learning a system's inclination (presuming the disk is coupled to the plane of orbits) is invaluable to a complete understanding of systems and the true mass(es) of their planets. Optical radial-velocity measurements are limited to providing a mass limit, M (sin i). Any additional constraint on i helps constrain the M (sin i) mass (and vice versa), which can then lead to constraints on density, composition, and ultimately, habitability.

Modern millimeter interferometers (e.g., Very Large Array (VLA)[4] and the Australia Telescope Compact Array (ATCA)) offer arcsecond resolution which can give information beyond a simple detection. Such capability could also shed qualitative light on a system's dynamical inclination, as shown in Lestrade et al. (2006). If the Gl 876 system were to contain a debris disk, the extent of which exceeds just $\sim$5 AU (which is our resolving power at 4.69 pc), then imaging observations could not only resolve the disk but also provide some geometric constraint on the inclination of the system. Of course the disk would have to have some "optical thickness" in order to observe any gradient consistent with an inclination.

Lestrade et al. (2006) found a disk around GJ 842.2, and refer to the one about Gl 182 found by Liu et al. (2004). Both disks are large enough ($\sim$100 AU) that they could be cleanly resolved by us. In their own quest for dust about our target Gl 876, Trilling et al. (2000) demonstrated their ability to discern inclination from their dust-disk observations of three *other* (G-type) stars using Cold Coronagraph with the Infrared Telescope Facility (IRTF), an instrument with less resolving power than the VLA and the ATCA. These precursor observations

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[4] The VLA is operated by the National Radio Astronomy Observatory, which is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

assured us that some general inclination information could be extrapolated from the appearance of any disk.

Other specific issues would be clarified with an improved understanding of dust disks about M dwarfs. Since dust has a short lifespan throughout a disk due to radiation pressure, Poynting–Robertson drag and gravity, it has to be regenerated to maintain the disk. This is done by the larger bodies which collide and so shed dust. Thébault et al. (2003) assert this for β Pictoris, and such a disk about Gl 876 would infer that a solar-like Kuiper-like belt might exist. While this relationship is expected in many disks, the planetesimal-dust relationship is not so clear for M dwarfs.

A lack of dust may also support the Greaves et al. (2004) hypothesis—that debris disks are uncommon around stars with close-in giants, presumably due to the short lifetimes of the parents of debris disks and a sweeping effect. For Greaves' hypotheses, Gl 876 is a good test. A disk would also specifically imply that rocky or icy bodies exist that are left over from the system's formation. A detection would also mean any planet-inferring asymmetries could be studied, as done for the HR 4796 disk (Wyatt et al. 1999). Certainly Gl 876's radial-velocity-derived 2:1 planetary resonance between Jovian planets "b" and "c" would lead one to seek additional correlations with any of the dust disks, such as Quillen & Thorndike (2002) reported in ϵ Eridani's ring. A general census of M-star dust disks would generally improve understanding of planet formation in general, as described in Apai et al. (2007).

Our search for thermal dust emission using the ATCA at 3 mm (94 GHz) and the VLA at 7 mm (43 GHz) produced a result that offered a series of useful insights. Specifically in Section 2, we describe our ATCA millimeter search, and in Section 3, we describe similar millimeter work done with the VLA. In Section 4 we describe our combined results, and then in Section 5 we discuss the implications of our null result.

2. OBSERVATIONS

We observed Gl 876 at both 3 and 7 mm with the ATCA and the VLA, respectively. Table 1 summarizes the observing details.

2.1. 3 mm Australia Telescope Compact Array Observations

Our 3 mm ATCA observations were conducted on JD 2453626 with five of ATCA's six 22 m antennas. Uranus was observed for 15 min as the primary calibrator. The secondary calibrator (PKS B2246 + 121) was then observed for 3 min and every fourth pair of target/secondary scans was followed by a "paddle" observation for absolute calibration. The total time on the target was 2.5 h with the IFs set at 93.5 and 95 GHz. Table 1 provides further details on the observations.

Data reduction was done using Multichannel Image Reconstruction, Image Analysis and Display (Sault & Killeen 1993, thereafter MIRIAD). The data sets from both intermediate frequencies (IFs) were edited and calibrated separately, but combined in imaging in order to maximize sensitivity. From this we produced a continuum image with a restoring beam of $2.75'' \times 2.75''$ with an rms noise floor at 0.9 ± 0.01 mJy beam^{-1}. Nineteen beams were the required minimum to cover the notional disk. We found no dust emission in the image and stopped reduction there. Our image covered the $\sim 55''$ extent of a notional $\sim$200 AU debris disk.

Table 1
ATCA and VLA Configurations

Parameter	ATCA	VLA
Date (2005)	Sep 12	Oct 14 (epoch 1)
Date (2005)	...	Nov 01 (epoch 2)
Julian date	JD2453626	JD2453658 (epoch 1)
Julian date	...	JD2453676 (epoch 2)
Frequency (GHz)	93.5, 95 ($\sim$3 mm)	43.315, 43.365 ($\sim$7 mm)
Mode	Continuum	Continuum
Elements	5 of 6	23 of 27
Bandwidth (MHz)	128, 128	50
Synthesized beam (arcsec^2)	2.75×2.75	1.47×0.93
Configuration	H168	DnC, D
Time on target (h)	2.5	3.4
Cycle (s)	10	80 (source), 30 (cal)
Epochs total (h)	1×4.5	2×2
$S_{3\sigma}$ (mJy beam^{-1})	0.9 ± 0.01	0.04 ± 0.003
Phase calibrator	PKS B2246 + 121	PKS B2246 + 121
Flux density calibrator	Uranus	3C48

2.2. 7 mm Very Large Array Observations

The 7 mm observations at National Radio Astronomical Observatory (NRAO) VLA took advantage of the dynamically scheduled period during array re-configurations. Epoch 1 was centered on JD 2453658 while epoch 2 was centered on JD 2453676. Again, Table 1 details the observations. For the first epoch, we used the hybrid DnC configuration with the north arm in the C configuration while the east and west arms were in the more compact D configuration. The second epoch occurred in full D configuration. For both of our VLA epochs, we used the full complement of available antennas (23 of 27 25 m antennas), and observed for a total 3.4 h. The synthesized beam of the VLA is $1.47'' \times 0.93''$. From the VLA data we produced a 512×512 pixel image with a spacing of $0.2''$ per pixel. The resulting $\sim 100 \times 100''$ image covers the $85''$ extent of a 400 AU debris disk. We used 30 beams to cover the linear extent of the potential disk.

We reduced the two epochs using Astronomical Image Processing System (Greisen et al. 2006, thereafter AIPS) and calibrated each epoch independently. We set the absolute flux density scale using a computed flux density of 0.53 Jy for the extragalactic calibrator, 3C48. Extragalactic calibrator source, PKS B2246 + 121, was used to estimate the instrumental and atmospheric phase fluctuations. We then applied phase corrections to the target source data. Gl 876 and PKS B2246 + 121 were then imaged at each epoch and concatenated into a single calibrated data set, and then imaged again. This resultant $35'' \times 35''$ contour image from the combined data showed no apparent emission. The VLA dirty map's rms noise floor was at 44 ± 2.5 μJy beam^{-1}. Finally, we applied a variety of uv-plane tapers and ranges besides these to extract any missed detection. This additional processing also failed to produce a detection.

3. RESULTS

In this section we use our upper limits on the millimeter emission from Gl 876 to constrain the properties of any debris disk orbiting it. Following standard formulae (e.g., Lestrade et al. 2006; Dent et al. 2000), we relate the flux density upper limits to the dust mass of an optically thin debris disk as

$$S_\lambda = \frac{M_{\rm dust} B(\lambda, T_d)\kappa}{D^2}, \tag{1}$$

where S_λ is the observed flux density at the given wavelength, $M_{\rm dust}$ is the dust mass in the disk, κ is the mass opacity, and $B(\lambda, T)$ is the Planck blackbody function for dust at temperature T. To provide a new constraint on the dust mass, we solved for mass using a 3σ noise floor.

For the temperature T of the dust particles, we assume a cool $T \approx 20$ Ks (see below), and also a less radiant energy is transferred to the dust than in the ideal case. Classic 1 μm sized Lambertian, spherical dust particles are generally assumed to have an albedo a_d for the dust where $a_d \approx 0.06$ (Brown et al. 1997; Jewitt et al. 1996; Luu & Jewitt 1996).

Since the dependence of temperature with a typical star-to-dust distance is $d^{0.5}$, the temperature at 30 AU outward will differ little, so we use one temperature to approximate the disk. But since M dwarfs are less luminous than G-type stars by $L \approx 0.1$ to $0.001 L_\odot$, they irradiate their circumstellar dust to a lesser $\leqslant$20 K than for the 35–50 K expected from dust about solar-like stars (Lestrade et al. 2006; Beckwith et al. 1990). The distance D is known with a high accuracy to be 4.69 pc. For the mass opacity in the most fundamental scenario, we presume the disk to be optically thin, and thus adopt a standard value of

$$\kappa = \kappa_0 \left(\frac{\lambda_0}{\lambda}\right)^{\beta}, \tag{2}$$

where $\kappa_0 = 1.0\,{\rm cm}^2\,{\rm g}^{-1}$. Owing to the wide disparity in postulated values for the opacity spectral index from 0.2 to 3.0, we will somewhat arbitrarily assume $\beta = 1$ as a starting point. Clearly our results will depend upon the assumed temperature and mass opacity. Should debris disks around M dwarfs turn out to have dust with, for instance, significantly lower mass opacity than that around earlier-type stars, we would have underestimated the dust mass in the Gl 876 system.

To prepare for a notional detection, we first assumed a disk diameter. At the distance of 4.69 pc, 1″ equals 4.69 AU, so the resolution (the number of divisions into which our telescopes' beams are divided) is equivalent to a linear scale of 12.7 AU. One possibility is that any disk would be unresolved because of its size. The debris disk is unlikely to extend much closer in toward the star than the outermost planet, which lies at a semi-major axis of 0.2 AU. Such arrangement allows a scenario where any disk would be unresolved with our instruments. However, guided by the known debris disks around M dwarfs (e.g., AU Mic, Gl 842.2, Gl 182), we shall assume a simplistic disk diameter of ~200 AU (or ~42.6″) here. This assumed disk would be well within the primary beams of the VLA and the ATCA and would even allow a disk to be resolved by the 4.69 divisions spread over the extent of the beam. In fact, we made images of a much larger > 100″ region as a precaution, so that we could detect any disk as large as even 225 AU in radius.

The assumed size of the disk becomes relevant to the value of the noise floors of the VLA and the ATCA, which provide a limiting value for observed intensity. These must be related to a flux density by assuming the area of a possible disk.

It is important to understand how (and when) inclination affects any detection above the noise floor. First it is statistically unlikely that the disk will be exactly face-on, nor edge-on. There exists a higher probability of being detected at some intermediate inclination. As with visual detections of edge-on transits at $i = 90°$, the geometric *a priori* likelihood of a single inclination is given by

$$P = 0.0045 \left(\frac{1\ {\rm AU}}{a}\right)\left(\frac{R_* + R_{\rm disk}}{R_\odot}\right), \tag{3}$$

where a is the semi-major axis of the orbit, R_* is the radius of the star and $R_{\rm disk}$ is the thickness of the disk, arbitrarily chosen here to be $\sim 3R_{\rm Jup}$. In the case of Gl 876, we also assume $R_* = 0.3R_\odot$, and for a notional disk we choose a to be a mean 100 AU. The result is ~2% for any given inclination about Gl 876, and a strictly geometric probability of ~40% for a range of i from 40° to 60°. Probabilistically, it is more likely that the Gl 876 disk is not edge-on but has some lesser inclination. The lesser the disk is inclined from "edge-on" to "face-on," the more the disk surface brightness decreases, thus making a null detection more likely as the flux density drops beneath the noise floor. Also, the disk must have some optical thickness (as described for younger disks in Takeuchi & Lin 2003, 2005) in order for us to have observed a gradient, and thus infer any tilt. As the study of M-star disks is relatively adolescent, it is not clear at this point how thick Gl 876's disk might be. In any event, such an opportunity for a disk to escape detection would be consistent with previous optical observations.

We solved for the dust mass using the rms noise floor for each radio telescope as a threshold, or a minimum detectable mass. The 3σ upper limit of 135 μJy on any undetected mass then becomes 0.0006 $M_\oplus$ for the area of a nominal 200 AU radius disk, for the more stringent VLA results.

4. DISCUSSION

As previously mentioned, Trilling et al. (2000) used NASA's IRTF Cold Coronagraph (CoCo) at 1.62 μm to search for a circumstellar disk around Gl 876, and produced their own null result for this system. However, their observations were less sensitive (3.6 times less so), and moreover were restricted to a narrow, 5″ (25 AU) beam width. Based on the size of the few red dwarf disks detected since their observations, this beam width was likely insufficient to assert that any M-dwarf disk does or does not exist about Gl 876. This beam easily could have missed a disk by looking at the cleared central hole in it.

Other observations of nearby stars done by Greaves et al. (2004) in fact provided additional impetus to do similar observations for Gl 876. From their observations they estimate that the ϵ Eridani and τ Ceti dust disks have 0.016 and 0.0005 $M_\oplus$ dust masses, respectively. As further comparison, AU Mic is a much younger M star at double the distance (~10 AU), and whose edge-on disk has a radius of between 50 and 210 AU. While the AU Mic disk is just one example, its minimum size also gave us confidence that any Gl 876 disk would also likely be resolved in our VLA and ATCA observations. Admittedly, strict comparisons between AU Mic and Gl 876 would be limited owing to the age difference, but seeing an older disk about Gl 876 would allow this age difference to be exploited in a first-time age comparison.

In the end, our improved beam width and sensitivity still proved insufficient to detect a larger, fainter disk similar to these, but we can say that our observations had a sufficient beam width to surely detect any Kuiper-like disk whose flux rose above the VLA noise floor of 44 μJy, if other factors did not cause the non-detection. In such a simplistic scenario we assert that no disk exists at the mass limit posed, if we assume that the dust is essentially optically thin.

The mass constraint that an upper mass limit puts on Gl 876 has dynamical implications worth exploring. The reasoning which allows resolved disks to be used to infer an inclination follows Lestrade et al. (2006). As noted earlier, they resolved a debris disk about GJ 842.2 at a shorter wavelength of 0.85 mm. This was done with sufficient resolution on

James Clerk Maxwell Telescope's Submillimetre Common-User Bolometer Array (SCUBA). Their results suggest that GJ 842.2 was generally inclined; for the same reasons inclination could be discernible for Gl 876.

The curious dynamics the Gl 876 system exhibits is due to its two outer Jovian planets which are locked in a 2:1 mean resonance, discussed in Laughlin et al. (2004, 2005), and Marcy et al. (2001). In 2002, Benedict et al. reported that their *Hubble* FGS astrometry of Gl 876 revealed an inclination of $i \approx 90^\circ$. However, the 2005 inner planet detection prompted Rivera et al. to revisit the inclination issue, which instead appeared to be $i \approx 50^\circ$. This more-tilted inclination was found to be consistent with 3σ photometry and radial-velocity transit reduction by one of us (Shankland et al. 2006), using reduction methods shown to be viable in Kane (2007). It is statistically likely that a positive dust detection would have probably suggested some inclination if there were some opacity—and thus support of one set of these conflicting optical observations.

On the other hand, a negative detection (as is the result here) suggests that a thin-dust mass could still exist about Gl 876 if the dust density were below the detection threshold of the individual VLA or ATCA resolution per pixel, or the overall upper mass limit. The, as yet, poorly understood dust density, temperature, spectral index, opacity, and optical thinness muddies our understanding of the mechanisms at play, and inclination would be a factor in each of these. Still, there are other possibilities for our null result. Another may be that the formation and evolution of systems (disks and planets) is different in M dwarfs. At the least, any unexpanded composition in the system would lead to misunderstood opacities, albedos, radii, or blackbody behavior.

As we have suggested, we also could have missed any disk owing to a less-than edge-on orientation that would have reduced the surface brightness in a less-than-transparent disk. Slipping under this threshold (and the noise floor of the VLA and the ATCA) at lower inclinations would be a result which favors the $i \approx 50^\circ$ scenario posited by Rivera et al. (2005) and Shankland et al. (2006). $i \approx 90^\circ$ of Benedict et al. could instead be correct if the disk were edge-on, but the mass is small, at 0.0006 $M_\oplus$. Our non-detection thus offers a two-variable constraint. Until the basis for a non-detection is constrained further, we can also at best *suggest* that Greaves' hypothesis appears to remain intact. More work clearly needs to be done to understand the properties of debris dust about M stars. Further, if these initial suppositions are correct, Gl 876's lack of dust also suggests few planetesimals in the system.

So our results suggest that further scrutiny of M stars is needed in order to understand how their systems differ from solar-type stars, particularly since M dwarfs have a demographic monopoly on the galaxy. More sensitive observations of this and other M stars would also begin a foundation for further numerical modeling of their disks (or lack thereof), as suggested in Deller & Maddison (2005). Certainly, any connection of dust to terrestrially-massed planets will fuel an interest in the increased scrutiny of M dwarfs. From the recent optical detections, the growing consensus is that red dwarfs may very well harbor the first discovered exo-Earths.

It is also worth mentioning that because of the low luminosity of M dwarfs (below $0.1L_\odot$) that leads to cooler dust about them, sub-millimeter or millimeter telescopes may be more sensitive than mid-infrared ones in detecting such planet-associated disks. We would encourage observations at these wavelengths to be explored further. In particular, we recommend that the six M dwarfs found with planets so far be comprehensively checked for dust, to include Gl 876 (with greater sensitivity than us), Gl 436 (Butler et al. 2004), Gl 674 (Bonfils et al. 2007), Gl 849 (Butler et al. 2006), Gl 581 (Udry et al. 2007), and GJ 317 (Johnson et al. 2007). Understanding the dust in such planet-bearing systems (as addressed in Dutrey et al. 2004) may be a key not just to making a first exo-Earth detection, but will more importantly offer a broader understanding of planets and their formation about the populous M-type stars.

5. CONCLUSIONS

We used the VLA and ATCA at millimeter wavelengths to search for thermal radiation from cool dust from the GL 876 system, and achieved the null result which improved upon previous limits. We observed no such emissions to 3σ, at the 135 μJy rms detection threshold. From this we calculated that any dust mass that might still be there had to be constrained to be a mass less than 0.0006 $M_\oplus$ for a nominal 200 AU radius disk. Our 3σ noise floor was established during our most sensitive observations with the VLA, and were consistent with our ATCA observations. This constraint does not generally contravene Greaves' postulation that a system's bodies sweep out regenerated dust. Since the disk inclination affects the surface brightness (depending on our "emerging" understanding of opacity, temperature, spectral index, density, and thinness), this lent qualitative constraints on how the system might be inclined. All things being equal a non-detection is more consistent with a lower inclination than a higher one.

For Gl 876, our result most importantly places basic constraints on the limits afforded by the instrumentation, and a more stringent upper $M_\oplus$ limit on any potential exo-debris there. While a lower-mass debris belt might be found for Gl 876 with greater sensitivity, the null observations we find thus far corroborate the effects of close-in Jovian planets. For Gl 876 in particular, we offer four solutions to explain this non-detection. Alternatively the system is less dusty or is optically thinner at the more detectable $i \sim 90^\circ$, or is "dustier" yet less detectable at some less edge-on inclination. The third possibility is that this red dwarf dust is comprised of material which is not similar to comparable disks about solar-like stars (e.g., has a different spectral index, thinness, temperature or opacity), and so evades detection for now. Finally, while it would be physically very unlikely, a disk (or instead a central hole) could have been larger than ~400 AU. Answers will remain enigmatic until a more sensitive dust study of Gl 876 is done, and more generally, a robust, low-bias census of M-star systems is completed.

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