The Role of Dust in Star and Planet Formation: Observations

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Abstract. The spectral and spatial distribution of dust emission from protostars and pre-main sequence stars forms the basis of much of our understanding of protostellar evolution. We describe why dust emission is so successful at tracing star formation activity, and review recent survey and imaging results. We also illustrate how dust destruction products trace the more energetic phenomena associated with star formation.

1. Introduction

Dust observations play an essential role in studies of star and planet formation. Varying amounts and distributions of dust are physically associated with stars throughout their pre-main sequence evolution, influencing the observed stellar properties. Angular momentum considerations argue that a protostar surrounded by a disk of gas and dust results from the collapse of a dense, rotating cloud core; in its earliest stages, the protostar/disk system is embedded in an infalling outer envelope (cf. Bodenheimer 1995). The new star becomes visible as infall, accretion in the disk, and the accompanying energetic outflow of material along the disk rotational axis, diminish with time, although a circumstellar disk may remain for much of its pre-main sequence lifetime (cf. Shu et al. 1993). At every stage, dust observations are critical to our understanding of the star formation process. For example, identification of heavily-obscured protostars and young stellar objects (YSOs) relies on measurements of far-infrared continuum emission from the associated warm dust particles (e.g., Wynn-Williams 1982), and long wavelength observations elucidate the physical properties of star/disk systems (e.g., Adams et al. 1990). The dust itself is severely affected by the proximity of star formation, modifying the chemical composition of the circumstellar environs. Energetic phenomena such as those associated with high-mass star formation can be traced through molecules liberated from grains by shock heating (e.g., Blake et al. 1987; Martín-Pintado et al. 1992). Grain coagulation is likely in the disks around solar-mass stars, and molecules can freeze out onto the grain surfaces (van Dishoeck et al. 1993). Since these latter disks resemble the primitive solar nebula, their grain properties may inform our understanding of planetary system formation (cf. Beckwith & Sargent 1991).

2. Millimeter and far-infrared dust emission

Thermal emission from dust particles traces regions of active star formation more effectively than molecular line radiation due to its radiative transfer. At a given frequency, ν, the dust optical depth, $\tau_{\rm d}$, depends only on the hydrogen column density, $N({\rm H}_2)$; the corresponding gas optical depth is proportional to $N({\rm H}_2)/T_{\rm ex}^2$, where $T_{\rm ex}$ is the excitation temperature of the molecular transition observed, and it has been assumed that the relevant energy levels are much less than $kT_{\rm ex}$ above ground. Thus, in the Rayleigh-Jeans regime, the peaks in dust emission, $B_\nu(T_{\rm d})(1-e^{-\tau_{\rm d}})$, coincide with the enhanced temperature and column density sites of embedded young stars, which is not necessarily the case for molecular line peaks. Furthermore, if both dust and molecular gas emissions are optically thin and thermalized, the contrast between regions of star formation and the ambient cloud is greater for particle radiation, since dust and molecular line emissivity scale as $N({\rm H}_2)T_{\rm d}$ and $N({\rm H}_2)/T_{\rm ex}$ respectively. The use of IRAS data to identify YSOs and to assess the star-forming properties of molecular clouds (Wood et al. 1995), as well as a submillimeter search for the cold, dense cores thought to precede the formation of protostars (Ward-Thompson et al. 1994), are recent examples of successful dust emission surveys.

Calculations based on far-infrared to millimeter-wave dust observations are, on the other hand, hampered by uncertainties in the value of the dust opacity, κ_ν, and its dependence on frequency; it is usually assumed that κ_ν follows a power law, $\kappa_\nu \propto \nu^\beta$. At $\nu = 10^{12}$ Hz, values of κ_ν ranging from 0.02 to 0.6 cm^2 g^{-1} can be found in the literature (e.g., Krügel & Siebenmorgen 1994; Pollack et al. 1994; Stognienko et al. 1995). The often-adopted value of 0.1 cm^2 g^{-1} therefore results in uncertainties of a factor of about 5 (cf. Beckwith & Sargent 1991). Theory suggests a value of $\beta = 2$ for sub-micron-sized particles in the general interstellar medium (e.g., Draine & Lee 1984). At the opposite extreme, large bodies such as planets have $\beta = 0$, leading to the suggestion that the value of β could serve as a diagnostic of grain size and hence of particle coagulation in protostellar (or planet-forming) disks (e.g., Miyake & Nakagawa 1993). Recent theoretical and laboratory studies of typical grain constituents, however, demonstrate that the value of β is also affected by grain shape and chemical composition (Pollack et al. 1994; Agladze et al. 1994, 1996). Despite these caveats, variations in β from source to source, or from interstellar to circumstellar material, should still reflect dust evolution. The fact that the nature of the evolution is not yet well-understood underscores the critical need for further investigations of far-infrared and millimeter-wavelength dust opacities.

3. Protostellar dust spectra

3.1. Classification schemes

Dust in the circumstellar environment of young stars contributes to their spectra in two ways: emission from dust in the disk adds a long-wavelength component to the stellar photospheric emission, while dust in any extended envelope reprocesses the emission from both the star and disk to longer wavelengths. The resulting spectral energy distributions (SEDs) then indicate the distribution of circumstellar dust and, perhaps, the way in which it is partitioned between disk

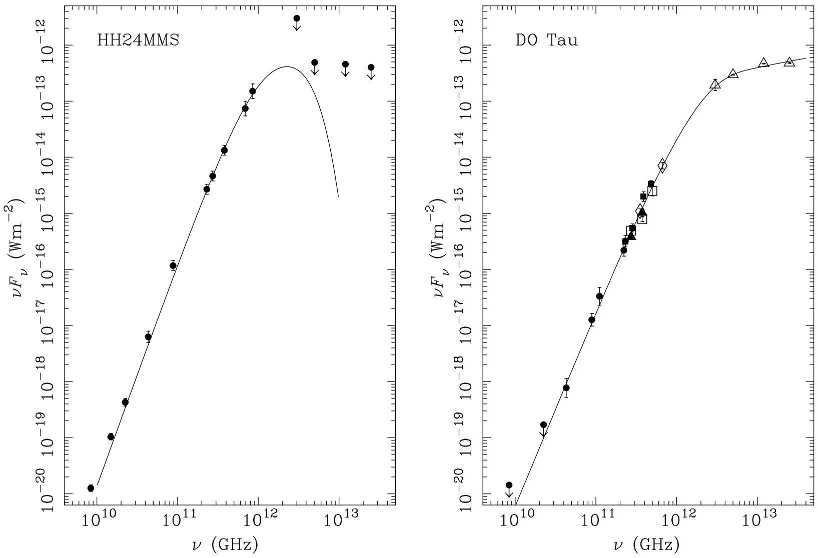

Figure 1. *Left:* the far-infared and millimeter dust emission from the Class 0 protostar, HH24MMS, and the model of an optically-thin envelope with $\beta = 1$ (adapted from Chandler et al. 1995). *Right:* the SED of the Class II source, DO Tau, together with the model of a circumstellar disk (adapted from Koerner et al. 1995; see also § 3.2).

and envelope (e.g., Adams et al. 1987). This suggests a means of assessing the evolutionary state of the forming star despite the obscuring dust and gas that prevent the determination of its age in the usual way, from its position in the Hertzsprung-Russell diagram. The scheme initially proposed by Lada (1987) used the near- to mid-infrared spectral index, $\alpha = d\log(\lambda F_\lambda)/d\log(\lambda)$, to separate sources into Class I ($\alpha > 0$), Class II ($-2 < \alpha \leq 0$), and Class III ($\alpha \leq -2$). An additional Class 0 was introduced by André et al. (1993) to accommodate objects whose radiation is detected largely at wavelengths longer than 100 μm. The bolometric temperature, defined as the blackbody temperature having the same mean frequency as the observed SED, has also been used to characterize YSOs (Myers & Ladd 1993). In terms of an evolutionary sequence, objects with particularly cold spectra, signifying a considerable amount of material in an extended envelope, are the youngest and dominate Classes 0 and I; next in age come Class II objects, exhibiting infrared to millimeter emission typical of a partially optically-thick dust disk; finally, Class III sources are almost at the zero-age main sequence and display only a small infrared excess over the blackbody of the stellar photosphere. However, the orientation of a star/disk system can alter its spectral appearance significantly, and Yorke et al. (1995) show that intermediate-mass Class I objects may be classified as Class II sources if viewed pole-on. In younger protostars the surrounding envelope reprocesses the radiation making it more isotropic, and disk orientation should be less important for Class 0 objects (Chen et al. 1996). Figure 1 shows example SEDs for the Class 0 protostar HH24MMS, and the Class II object DO Tau.

3.2. Surveys for circumstellar dust disks

In a number of surveys of millimeter and submillimeter continuum emission from optically visible YSOs sufficient circumstellar material is detected that the stars would be completely obscured unless the dust is asymmetrically distributed (e.g., Adams et al. 1990; Beckwith et al. 1990; Mannings & Emerson 1994; André & Montmerle 1994; Osterloh & Beckwith 1995). The SEDs of these objects can in fact be fitted by models of the dust emission from flat circumstellar disks, allowing estimates of disk properties. In particular, the dust emission is largely optically thin at millimeter wavelengths and can therefore be used to determine the disk mass if the temperature distribution and dust opacity are known. As already discussed, the latter quantity is somewhat uncertain, but power law temperature profiles, $T(r) \propto r^{-q}$, can be derived from the SEDs at wavelengths shorter than $\sim 100\ \mu$m, where the disk emission is optically thick (e.g., Beckwith et al. 1990). Approximately 50% of pre-main sequence, solar mass stars – T Tauri stars (TTs) – appear to be surrounded by disks, with masses (gas plus dust) in the range 0.002 to 0.1 $M_{\odot}$, and radii of approximately 100 AU. The measured value of q lies in the range 0.5 to 0.75, somewhat flatter than expected for standard accretion disks or disks which reprocess the light from the central star (Pringle 1981). A number of hypotheses have been put forward to account for the anomaly, the most successful involving some form of dust envelope around the star/disk system (e.g., Natta 1993; Calvet et al. 1994). Envelope and disk configurations are also often invoked to explain the SEDs of the more massive counterparts of T Tauri stars, the Herbig Ae/Be stars (Hillenbrand et al. 1992; Hartmann et al. 1993; Natta et al. 1993; Henning et al. 1994; Mannings 1994; Di Francesco et al. 1996).

In the Rayleigh-Jeans regime ($\lambda \gtrsim 1$ mm for the temperatures expected in circumstellar disks) the observed continuum flux density should have the form $F_\nu \propto \nu^s$, where the spectral index $s = 2 + \beta$, enabling a determination of β (but see Thamm et al. 1994). Measurements of β using this method, and fits to spectra of circumstellar disk models, typically give $\beta \lesssim 1$ for TTs (Beckwith & Sargent 1991; Mannings & Emerson 1994). Figure 1 shows the spectrum of DO Tau, a young T Tauri star with an optical jet (Hirth et al. 1994) oriented perpendicular to a disk of gas and dust (Koerner & Sargent 1995); the new 7 mm capability of the VLA has extended the wavelength coverage into a region of the spectrum where thermal emission from dust is reliably optically thin. For DO Tau, $\beta = 0.4 \pm 0.2$ directly from the spectral index, and $\beta = 0.6 \pm 0.3$ from fitting a model of a thin circumstellar disk (Koerner et al. 1995). Such a low value of β could indicate evolution such as grain growth in circumstellar disks, compared to the interstellar medium (cf. Mannings & Emerson 1994). Considerably more observations of disk continuum emission at wavelengths where it is unambiguously optically thin are required to support this hypothesis.

Deficits in TTs and Herbig Ae/Be star SEDs relative to the expected emission at near- and mid-infrared wavelengths have been interpreted as gaps, or optically-thin regions, in the inner parts of their disks, possibly due to clearing by unseen companions (e.g., Beckwith et al. 1990; Lada & Adams 1992; Strom et al. 1993). These may, however, be due to the inadequacy of the vertically-isothermal disk models used to interpret the data; more realistic temperature structures combined with standard mid-infrared dust opacities can also explain some of the observations (Boss & Yorke 1993; Sonnhalter et al. 1995). On the other hand, an overall decrease in near-infrared disk emission has led Dutkevitch (1995) to suggest that TTs more than about 3 million years old no longer have most of their circumstellar material in the form of micron-sized dust particles. This result clearly has important implications for the formation timescales of larger bodies in planetary systems (Wetherill 1990; Podosek & Cassen 1994). The presence of a companion star also appears to influence disk survival. Surveys show that binary systems with separations less than typical disk radii ($\lesssim$ 100 AU) consistently have lower millimeter/submillimeter fluxes than wider binaries or single stars (Beckwith et al. 1990; Osterloh & Beckwith 1995; Jensen et al. 1994, 1996a).

4. Images of dust emission: extended and compact structure

So far, we have concentrated on dust observations made using single telescopes. Since the resulting spatial resolution is relatively low, for the most part $\gtrsim 11''$, these observations are preferentially sensitive to the extended envelopes around the forming stars. In contrast, aperture synthesis imaging filters out larger-scale structure, such as the envelope and associated cloud, enabling us to discern the more compact emission from protostellar disks. In their IRAM 30-meter survey of the ρ Ophiuchi cloud at $\lambda = 1.3$ mm, with $\approx 12''$ resolution, André & Montmerle (1994) found that emission from the younger, Class I objects was extended, while that from Class II T Tauri stars was unresolved. However, the measured absolute flux densities for both Classes are similar, perhaps reflecting an evolutionary sequence in which the circumstellar structure gradually changes from envelope-dominated to disk-dominated. Higher resolution interferometer maps demonstrate that disks do commonly accompany Class 0 and Class I protostars (Terebey et al. 1993), although their 3 mm continuum emission is typically much weaker than from visible T Tauri stars (Ohashi et al. 1996). It is worth noting that the spectral index of the disk component of the emission must be lower than in the envelope in order to explain the 2.7 mm interferometer flux densities, and could be the result of a lower value of β in the disk (Terebey et al. 1993; see also Chandler et al. 1995).

At millimeter wavelengths, synthesis imaging techniques have been essential in isolating circumstellar dust disks from the surrounding envelope material (e.g., Keene & Masson 1990; Chandler et al. 1995). However, to measure directly the structure of disks with diameters of 100–200 AU requires resolution of an arcsecond or better in nearby star forming regions, and until recently the disk continuum emission was rarely resolved. The situation is now improving as the baselines of the existing millimeter arrays are extended (Mundy et al. 1996; Looney et al. 1996), and submillimeter interferometry becomes viable. Using the fixed baseline from the Caltech Submillimeter Observatory to the James Clerk Maxwell Telescope at a wavelength of 870 μm, disk radii of 80 and 60 AU have been measured for the protostars L1551-IRS5 and HL Tau respectively (Lay et al. 1994). These values agree well with those derived from models of spectral energy distributions, and are consistent with the presumed size of the primitive solar nebula (Podosek & Cassen 1994). The fraction of single-dish emission in the disk component increases from 25% in L1551 to 100% in HL Tau, which is probably

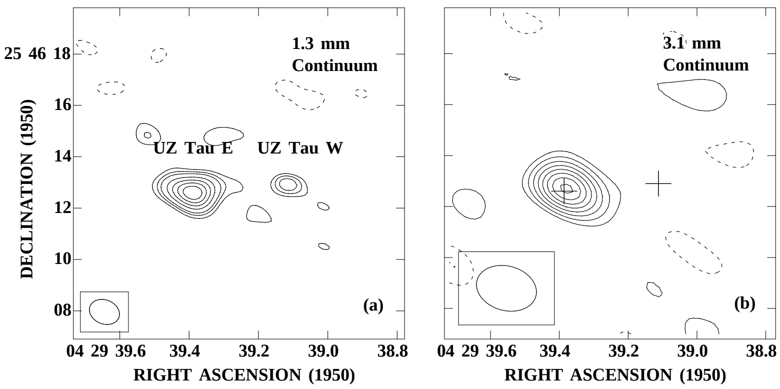

Figure 2. Contours of (a) 1.3 mm and (b) 3.1 mm dust continuum emission from UZ Tau (Jensen et al. 1996b). Emission from the 50 AU binary UZ Tau W is significantly depressed relative to the 0.1 AU binary UZ Tau E.

somewhat older (but see Stapelfeldt et al. 1995). A similar analysis of the Class 0 protostar VLA 1623 has identified a dust disk comprising only about 10% of the total flux (Pudritz et al. 1996), and provides further support for the evolving envelope/disk hypothesis since a more massive envelope would be expected in this much younger object. High-resolution images of T Tauri stars indicate that their circumstellar disks may have rather flatter surface density distributions than are expected for standard accretion disks (Dutrey et al. 1996; Mundy et al. 1996). Models of the distribution of light scattered off dust grains in the HH 30 disk lead to similar conclusions (Burrows et al. 1996). Combined with the flat temperature distributions described above, it seems that the observations are beginning to provide strong constraints on the structure of circumstellar disks.

Disks are also likely to be affected by the presence of multiple stars (Artymowicz & Lubow 1994). Resolved circumbinary continuum emission has in fact been detected around GG Tau, and modeling suggests that an inner hole of radius 180 AU has been created as a result of a stellar companion, in good agreement with binary disk theory (Dutrey et al. 1994). Another demonstration of the effect of multiple stars was recently reported for the young binary system UZ Tau (Jensen et al. 1996b; Figure 2). Imaging at $\lambda = 1.3$ mm with $1''$ resolution shows that emission from UZ Tau W, a ~ 50 AU binary, is significantly depressed relative to UZ Tau E, suggesting that its circumstellar disk has been severely disrupted by the presence of the companion. UZ Tau E has itself recently been identified as a spectroscopic binary with a separation ~ 0.1 AU (Mathieu et al. 1996), which seems not to influence the disk structure at larger radii.

In regions of high extinction, such as young protostellar systems, measurements of polarized dust emission are the only method of establishing the direction of circumstellar magnetic fields. Current theories predict that optical jets and molecular outflows may be driven by magneto-hydrodynamic disk winds

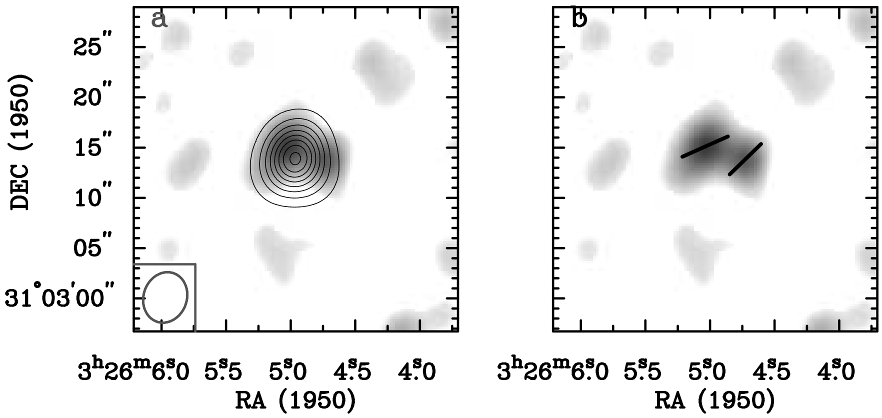

Figure 3. The intensity of the linearly polarized emission from NGC 1333/IRAS 4A (greyscale) plotted with (a) the total intensity (contours), and (b) the polarization vector at the position of the two peaks (from Akeson et al. 1996). The magnetic field direction is perpendicular to this position angle. The well-collimated outflow is directed N-S close to the source, bending to $\sim 45°$ on larger scales.

(cf. Königl & Ruden 1993), but direct observations of the behavior of the magnetic field in the dense cores where stars form has until now been impossible. Single-dish measurements of the millimeter dust polarization typically give a linear polarization of a few percent (e.g., Tamura et al. 1995; Holland et al. 1996). The potential for higher resolution interferometric imaging of the polarized dust emission is illustrated by very recent observations of the young protostar NGC 1333/IRAS 4A (Figure 3) which show clearly that the magnetic field is indeed aligned with features in the high-velocity molecular outflow (Akeson et al. 1996). Continuing observations of this kind will add considerably to our understanding of the cloud collapse stage of star formation, as well as of the origin of energetic outflows.

5. Dust destruction in star forming regions

5.1. Hot cores

The proximity to a strong radiation source, or the passage through a shock, may severely disrupt and even destroy dust grains. Both situations occur at sites of star formation, and the dust destruction products can be used as diagnostics of these more energetic phenomena. The hot core in Orion, a dense clump of gas and dust approximately 500 to 1000 AU from the luminous radio source "I" in the Orion-KL region, is one such example. Many chemical species, in particular nitrogen-bearing molecules, have abundances at the hot core several orders of magnitude higher than in the general interstellar medium (e.g., Blake et al. 1987). The excitation temperatures of the various species increases inversely with the projected distance from source I (Blake et al. 1996), and it is thought that the enhanced molecular abundances represent the release into the gas phase of molecules in grain mantles, caused by the heating of the dust by radiation from source I (see also Wright et al. 1996). Enhanced abundances, particularly of CH_3CN and NH_3, have been observed in other regions of high-mass star formation (e.g., W3(H_2O): Helmich et al. 1994; G34.3+0.15: Millar et al. 1995; G10.47+0.03, G31.41+0.31: Olmi et al. 1996), and are interpreted as the same phenomenon.

5.2. Protostellar jets

In the more extreme conditions found in interstellar shocks, the dust grains may be completely vaporized (e.g., Neufeld & Dalgarno 1989; Flower et al. 1996). SiO can then form in the gas phase from the dust destruction products, and it is this mechanism which is thought to account for the anomalously high abundances of SiO observed associated directly with the outflow from source I in Orion (Blake et al. 1987; Chandler & De Pree 1995), L1448 (Guilloteau et al. 1992), and in several other outflow sources (e.g., IRAS 03282+3035: Bachiller et al. 1994; L1157: Zhang et al. 1995). In Figure 4 the correspondence between the SiO emission and shocked gas traced by molecular hydrogen emission is illustrated for the stellar jet HH211 in Perseus. To date, strong SiO emission from low-mass protostars has been detected only in the youngest objects. The excitation temperatures in the SiO jets are considerably higher than is typical for the swept-up material in molecular outflows (Martín-Pintado et al. 1992; Richer & Chandler 1996), and may provide an extremely important clue to the acceleration mechanism of ambient cloud material in the early stages of protostellar jet formation.

6. Observations of dust: the future

One of the limitations of the existing far-infrared survey data obtained by IRAS is that they are not sensitive to objects whose SEDs peak beyond 100 μm, i.e., the youngest and most deeply embedded protostars. This presents problems in assessing the relative lifetimes of the early evolutionary phases compared with the Class I, II, and III objects which have been extensively studied, since the current samples of younger sources suffer severe selection effects. Large-scale surveys of molecular clouds at wavelengths also sensitive to cold dust are needed, and the new submillimeter imaging instruments such as SCUBA (on the James Clerk Maxwell Telescope) and SHARC (at the Caltech Submillimeter Observatory) provide for the first time the prospect of a statistically complete analysis of star formation. The current and proposed space-borne observatories such as ISO, SOFIA, and SIRTF will be essential for completing measurements of spectral energy distributions in the far-infrared. Sub-arcsecond imaging of dust in circumstellar disks will soon be routinely available with the Smithsonian Submillimeter Array currently under construction on Mauna Kea, Hawaii, and with the existing millimeter arrays. In the long term, a larger instrument, comparable to the VLA at millimeter and submillimeter wavelengths, is likely to hold the key to a comprehensive understanding of the role of dust in star and planet formation.

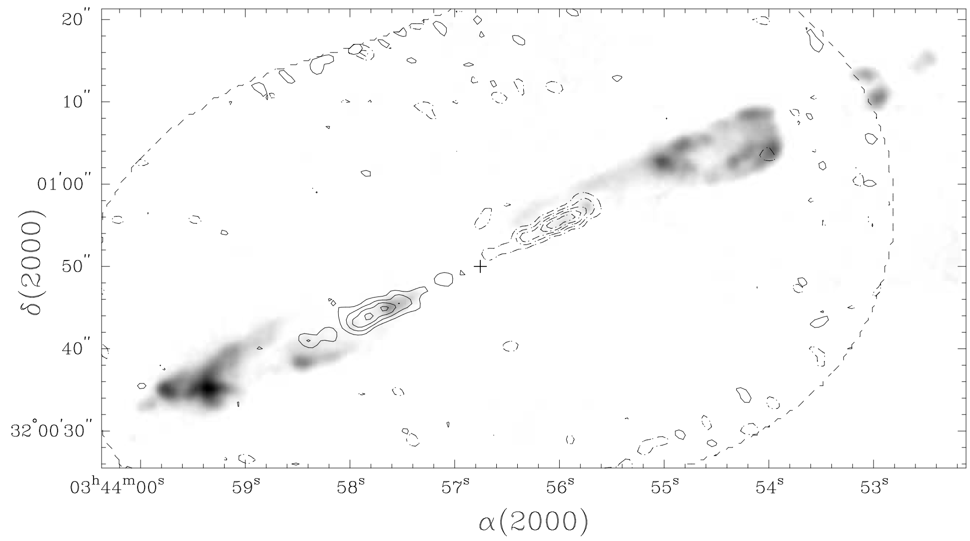

Figure 4. Redshifted (solid contours) and blueshifted (dot-dash contours) of the SiO(1–0) emission from the protostellar jet HH211 (Richer & Chandler 1996), overlaid on a logarithmic greyscale of the H_2 emission from McCaughrean et al. (1994). The position of the millimeter continuum source is marked by a cross. The abundance of SiO in the jet is thought to be enhanced by the destruction of dust grains in shocks.

The prognosis for understanding evolutionary traits in the dust grains is less optimistic at present, although the potential for β to be a diagnostic of grain evolution is extremely exciting, and could prove to be very important in constraining models for the formation of planetesimals in circumstellar disks. Extensive surveys of the value of β in disks at all stages of protostellar evolution are needed, and continuing theoretical, observational, and laboratory measurements are required to establish the absolute value of the dust opacity unambiguously.

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