INFALLING PLANETESIMALS IN PRE-MAIN SEQUENCE STELLAR SYSTEMS

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Recent ultraviolet and optical observations have identified a large class of late-stage, pre-MS and zero-age main sequence (ZAMS) stars having circumstellar material with a disklike geometry. These structures possess many of the characteristics expected for objects that will eventually evolve into planetary systems, including high velocity, infalling gas features exhibiting prominent departures from "cosmic" abundances. A complementary view of the near-stellar disk material can be obtained by probing the mineralogy of the small grains via infrared spectroscopy. We review the ground-based and ISO data on the small-grain components of the inner disk regions. The available models for infall activity in these stars are compared with the spectroscopic data of the gas and dust, and the mineralogy of interstellar dust particles.

I. INTRODUCTION

These are exciting times in the study of planetary system formation with a steadily expanding inventory of exo-planet detections, and imaging of dust disks around nearby young and main sequence stars. While these discoveries imply that our Solar System is far from unique, linking the data for the protoplanetary and debris disks to mature planetary systems requires a demonstration that disk evolution proceeds via planetesimal production and growth to the formation of planets (Beckwith & Sargent 1996, see chapter by Beckwith et al., this volume). Theoretical studies of planet formation indicate that planetesimals grow, via runaway accretion, to lunar-sized (≈2000 km) embryos in 10^5 years (see, e.g. Boss 1996). Recent gas giant planet formation studies have suggested that most of the action in planet formation occurs over 1-16 Myr, with formation of planets similar to Jupiter in t≤10 Myr (Pollack et al. 1996), within the time interval that infrared (IR) and optical emission line studies have demonstrated that circumstellar material remains detectable around both solar mass and intermediate mass stars (Strom et al. 1989; van den Ancker et al. 1997). Direct imaging of exo-planetesimals is not feasible with current and foreseeable technology, since such bodies have substantially less surface area than micron-sized grains distributed in a disk, and thus are inefficient IR emitters. However, such bodies may be indirectly detectable.

A. β Pictoris: The prototypical disk system

The nearby (d=19.28 pc, t≥8 Myr (Crifo et al. 1997)) β Pic system provided the first indication that exo-planetary systems are among field stars near the Solar System (see chapter by Lagrange et al., this volume). As a result of 15 years of intensive study following its detection as an IR excess source by IRAS and subsequent imaging of the disk (Smith & Terrile 1984), the β Pic system is currently the best-studied external disk system, with strong indications that the disk already harbors one or more giant planets (Heap et al. 1999; Artymowicz 1997). The star also possesses IR silicate emission features resembling cometary materials (Knacke et al. 1993), and optical polarization (Gledhill et al. 1991) similar to the zodiacal light in our Solar System (Leinert et al. 1981). β Pic also has spectroscopic absorption features due to circumstellar gas at rest with respect to the star and redshifted components in UV and optical spectra (Ferlet et al. 1987, Hobbs 1987). These components have been interpreted as absorption by the comae of swarms of comet-like bodies. Multi-year fluctuations in the frequency of exo-cometary activity may point to perturbations produced by gas-giant planets (Deleuil et al. 1995; Mouillet et al. 1997). The spectroscopic signatures for the presence of planets are of particular interest, since such markers for the presence of planets can sample a larger volume of our Galaxy than can be surveyed by imaging techniques.

B. The Other Intermediate-Mass Stars

While its exact age remains controversial, there is general agreement that β Pic is a main sequence (MS) star (Crifo et al. 1997; Lecavalier des Etangs et al. 1997; Jura et al. 1993; Backman et al. 1997). If the infall activity in the β Pic disk is a remnant of earlier disk evolutionary phases, similar activity must be present around other young, A and B stars, and should also be detectable in association with young solar analogs, the T Tauri stars (TTS).

There is a population of pre-main sequence (PMS) to ZAMS A and B stars which are young β Pic analogs, the Herbig Ae/Be (HAeBe) stars (Waters & Waelkens 1998; Pérez & Grady 1997; Thé et al. 1994). The nearest HAeBe stars are 100-140 pc from the Solar System (van den Ancker et al. 1997, 1998a). These stars are surrounded by circumstellar dust and gas disks with typical radii of several hundred AU (see Natta, Grinin, & Mannings, this volume, for a discussion of disk imaging, masses, and the gas content; Mannings et al. 1997; Mannings & Sargent 1997; Henning et al. 1998), comparable in diameter to lower mass, dust disks around MS Systems with typical radii of 100 to several hundred AU (Holland et al. 1998; Jayawardhana et al. 1998; Koerner et al. 1998; Greaves et al. 1998). Compared to the TTS, the HAeBe stars offer a number of advantages for line-of-sight absorption studies similar to the β Pic studies. First, the HAeBe stars have substantially higher T_{eff} and L_* than young Suns. Coupled with the minimal foreground interstellar extinction and low circumstellar optical depths toward the nearest HAeBe stars, the luminosity of these objects permits us to carry out line-of-sight studies from the IR through the far-UV. The UV-bright HAeBe stars are also quiescent, with little indication of stellar activity, continuum veiling or any of the other complications of T Tauri spectra. HAeBe stars rotate more rapidly than young Suns, resulting in washing out of the photospheric absorption features and enhancing of the contrast of circumstellar features against the stellar background. To date, the bulk of the UV absorption line studies of circumstellar gas around young stars, which provide a wider range of elemental diagnostics than are accessible in the optical, have been carried out for HAeBe stars and a few nearby, ostensibly main sequence A and B stars with circumstellar gas.

II. THE SPECTROSCOPIC DATA

The first detections of redshifted absorption features in the spectra of HAeBe stars date to 1992 (Welty et al. 1992; Graham 1992; Pérez et al. 1993; Grady et al. 1993, 1996a,b; Grinin et al. 1994, 1996).

The inventory of stars with infall detections continues to expand. At the time of writing, 13 of 33 HAeBe stars with IUE data have infall detections, as well as similar activity in 3 non-emission B stars (Grady et al. 1996a), and optical detections toward an additional 12 stars (Grady et al. 1996; Grinin et al. 1996, 1994; Graham et al. 1992). The optical detections are preferentially associated with objects with a history of large amplitude ($\Delta V > 2$ mag.) photometric and correlated polarimetric variability (Bibo & Thé 1991; Herbst et al. 1994, who termed such systems UXORs after the class prototype UX Orionis, see the paper by Natta et al., this volume; van den Ancker et al. 1999). At this time redshifted features have been observed in *all* of the better monitored UXORs, and have subsequently been detected in one star, AB Aur, not currently exhibiting such variability, but with a history of large amplitude light variations in the 1920s (Grady et al. 1999a).

The close association of the UXOR phenomenon and infall activity suggests that the phenomenon is associated with the circumstellar disk. Both the IUE data (35% of sources) and the frequency of large amplitude variability among the Hipparcos HAeBe stars (35% van den Ancker et al. 1998) are consistent with detection of disk material up to 15° above the disk mid-plane, if we model the disks as having constant opening angles. More flattened distributions are possible if the disks are flared, as has been observed in HST observations of T Tauri stars (McCaughrean et al., this volume). These limits are compatible with the inclination data provided by the *polarimetrically* identified systems with infall, and suggest that infall activity is restricted to the disk plane among the HAeBe stars (Grinin & Rostopchina 1996; Grady et al. 1996a, 1997, 1999a,b). The true inclination dependence of infall activity in these stars is likely to be further constrained as data on disk inclinations, based on imaging of the disks, are obtained.

A. Characteristics of the Infalling Gas

Infalling, circumstellar gas is observed in a wide range of atomic ions in the spectra of HAeBe stars and related MS stars (Fig. 1-3). Redshifts as large as 200-400 km s^{-1} are typical, with velocities as high as 500 km s^{-1} in some cases. For the HAeBe stars, redshifted absorption is usually observed in tandem with absorption at the stellar radial velocity and blueshifted absorption features due to a stellar wind. The strength of the absorption, velocity range over which infall can be detected, and ions exhibiting infall are typically reduced in the MS stars with "shell" spectra, relative to the PMS stars. In a number of systems (HD 100546, AB Aur, HD 37806) infalling gas is observed in transitions of higher excitation gas than the outflowing material, suggesting that the infalling gas has substantially higher density than the high velocity wind material. In some cases, the neutral atomic gas is restricted to the infalling material (Fig. 2).

Multiple ionization stages, including neutrals through triply ionized species, of a given element (e.g. C I, C II, C IV, see Fig. 2) are usually seen *in the same velocity range*, and frequently with similar or only slightly different profiles. Triply ionized species (C IV, Si IV) can only be produced by collisional ionization in the spectrum of a late B or A type star (Bruhweiler et al. 1989). While there is a tendency for the neutral atomic gas features to be observed at lower velocities (typically $\leq$150 km s^{-1}), and higher ionization stages can range up to the maximum observed velocity, we do not see a trend of progressive ionization with increasing infall velocity.

When normalized either by a photospheric comparison spectrum or by a spectrum of the same star in a low infall state, the infalling gas profiles have uniform absorption depth for a given ion, largely independent of transition excitation and oscillator strength. The infalling gas features usually show flat absorption troughs which are substantially above the instrumental scattered light levels. These features are similar to those seen toward β Pic (Vidal-Madjar et al. 1994; Vidal-Madjar & Ferlet 1995) and have been interpreted as detection of optically thick, saturated absorption from gas clouds which do not fully obscure the star. The depth of the saturated absorption measures the percentage obscuration of the stellar disk, or covering factor, and can be used to probe the spatial extent of the gas clouds in different elements.

B. Composition Constraints on the Infalling Material

We have begun to probe the composition of the infalling material. While the high optical depths and saturation of the infalling gas profiles preclude conventional column density estimates, departures from expected abundances can be noted where absorption in strong transitions of elements is missing or anomalously weak. This approach to constraining the composition of the infalling material was first exploited by Grinin et al. (1994) and Sorelli et al. (1996). They noted that the detection of infalling Na I with high covering factors in the absence of heavy continuum line blanketing and prominent infall signatures in transitions of H I and He I indicated that the infalling material showed signifcant departures from cosmic abundances. Subsequent analysis of high infall state data for HD 100546 showed that the infalling material in that system was underabundant in Fe, Cr, Mn, and Al relative to Si, Mg and Zn (Grady et al. 1997), with Cr underabundant relative to Zn by at least a factor of 12. The UV data for this system implied that any silicates in the disk should be strongly Mg-rich, a result borne out by ISO LWS data (Malfait et al. 1998a).

Similar analyses have been carried out for the younger HR 5999 (0.6 Myr), AB Aur (2-4 Myr, Grady et al. 1999a), HD 163296 ($4^{+6}_{-2.5}$ Myr, Grady et al. 1999b), and HD 100546 (t$\geq$10 Myr) systems (Fig. 3). These systems exhibit prominent UV line blanketing due to Fe II transitions, and show no indication of underabundances in the siderophile and super-refractory elements. Covering factors for the magnesium or silicon ions tend to be comparable, and typically larger than for the iron ions, suggesting that the silicates in these systems may also be Mg-rich. The effect is not, however, as dramatic as for HD 100546. A larger sample of objects is needed to determine whether the trend of more prominent departures from cosmic abundances is an evolutionary effect for all young A and B star systems, or is peculiar to HD 100546.

C. Variability and Synoptic Observations

At present, only a few HAeBe stars have been observed on a daily or higher frequency basis, as opposed to more sporadic observations separated by months to years. The dense time series indicate that infall events are comparatively frequent in young HAeBe stars, and become more sporadic with increasing system age (Table 1). Episodes of enhanced infall typically last tens of hours (>35 hours, AB Aur, Fig. 4; >48 hours, BF Ori, de Winter et al. 1999; 24-48 hours, HR 5999, HD 142666; and 15-$\geq$45 hours, HD 163296, Grady et al. 1999b). The UV data provide some suggestion that episodes of enhanced infall are correlated with suppression of the high velocity (v$\geq$200 km s^{-1}) portion of the stellar wind, although lower velocity wind material is apparently unaffected.

III. MODELLING THE INFALL ACTIVITY

A number of models for accretion activity have been proposed for PMS Stars. In this section we review their applicability to the data.

A. Accretion Models

Star formation studies predict that the star grows in mass by accretion of material from a circumstellar disk which can be modelled as a classical accretion disk. This disk may be embedded, especially if the system is still comparatively young, in a larger, and possibly spherical envelope which may continue to rain material onto the disk, but with velocities below 1 km s^{-1}(Bodenheimer 1997; chapter by Mundy et al., this volume). Higher infall velocities and ionization stages are expected if the infall is accompanied by classical accretion disk activity. Early on, the bulk composition of the disk should resemble the molecular cloud from which it formed. Accretion of material onto the star at this point should, therefore, be dominated by those elements which are numerically most abundant in the disk, and the infalling material should closely follow the stellar abundance pattern. This implies that the derived abundances should be dominated by volatiles such as hydrogen and helium.

The magnetospherically-channelled accretion models (see Edwards et al. 1994) further predict that the bulk of the accreted material should have remained in the gas phase since disk formation, and that accretion should be modulated by the stellar rotation period, with the bulk of the accretion onto localized hot spots on the stellar photosphere. An important prediction of this model is that accretion activity should be observed at high latitude, and not be restricted to the disk mid-plane. This latitude independence is observed in classical TTS (Edwards et al. 1994) where there is also the expectation that the outer convective region in the stellar atmospheres should produce magnetospheres.

B. Star-Grazing Comets

The star-grazing cometesimal hypothesis was initially developed for β Pic (Beust, et al. 1990; Beust et al. 1996) to account for the presence of episodic, high velocity infall in a wide range of transitions of refractory elements (see Lagrange et al., this volume). This model predicts that a large velocity extent should be seen in any ionic species for which the ratio of the radiation pressure force to that of gravity, $F_{rad}/F_{grav} \geq 1$. This model also predicts that infall events should be preferentially detected in the disk plane, unless the system is both sufficiently old that an Oort cloud has been populated and there has been enough time for bodies resident in an Oort cloud to be perturbed into cometary orbits. ($t \approx 10$ Myr, with full isotropization in ≈ 100 Myr, see Duncan et al. 1987). The model also predicts that any species which can be produced by outgassing of primary volatiles and/or the dissociation and subsequent vaporization of grain materials should be represented in the infalling material, and that the abundance pattern should resemble cometary materials rather than the full stellar abundance pattern (see Greenberg 1998). For older systems, resonances introduced into the disk by the presence of massive planets are expected to cause episodic infall events and perturbation of swarms of bodies (Roques et al. 1994; Lescavelier des Etangs et al. 1996; Mouillet et al. 1997). The swarms should produce absorption features at characteristic velocities which are a function of the orbital characteristics of the perturbing bodies.

C. Comparison with the Data

Infalling material with velocities up to 60% of the free-fall velocity from infinity, in both the HAeBe stars and in the older A-shell star systems, is preferentially observed close to the stellar equatorial plane (Grady et al. 1996a,b; 1997; 1999a,b). Infall activity in the HAeBe stars does not exhibit the latitude independence seen in young solar analogs (Edwards et al. 1994). The infall events do not seem to show any sustained, periodic modulation on the stellar rotation period (Grady et al. 1999a,b). Detection of multiple ionization stages over the same velocity range (Fig. 2) is consistent with the behavior of bow shocks. The presence of infall activity associated with stars having extremely inhomogeneous disks (the UXORS, see discussion by Natta et al. this volume), and the similarity of the infall activity in ionization, velocity, and profile shapes to that observed toward MS stars with debris disks, such as β Pic, suggests that the infalling gas is not associated with accretion disk activity.

The presence of neutral atomic gas species at velocities of order 100 km s^{-1} (e.g. deep in the star's gravitational well) where such species should have extremely short photoionization lifetimes, of order seconds to minutes (Sorrelli et al. 1996) provides one of the most important clues to the source of the infalling material. The presence of such species is consistent with *in situ* production of the gas. Transport to the observed location of the neutral atomic material in the form of diatomic gases (such as H_2 and CO) is excluded because the photodissociation lifetimes for these species are even shorter than the photoionization lifetimes of their daughter products. An origin in grains is implied both by the prominence of refractory elements in the infalling material, and small covering factors for primary volatiles (e.g. He I), and by the expectation that such elements will be preferentially depleted onto grains under the conditions of a protoplanetary disk (Owen 1997) around HAeBe stars. Thus, the infalling material is likely to be preferentially associated with grains and/or larger solid bodies.

The covering factor data also provide additional information on the nature of the solid material. There is a trend for refractory species (Mg II, Si II, Ca II, Al II, Al III) to have similar covering factors to the carbon ions. Both sets of ions can have large covering factors (60-80%). Semi-refractory species such as Zn II and S II (when detected) exhibit smaller covering factors, roughly comparable to the iron ion covering factors. N I and He I have the smallest covering factors, with the He I data consistent with obscuration of at most 10% of the stellar disk. If we assume that the bulk of the iron is associated with semi-refractory grains such as FeS and FeO, the Zn with ZnS, and the carbon associated with refractory organic materials, the covering factor data suggest a good correlation with with the sublimation temperatures of simple minerals, under the assumption that the parent bodies have not been substantially heated above 350-400 K over the evolutionary lifetimes of the stars ($\approx$1-10 Myr). If the N I and other volatile (see §5 below) gas species (O I, H I, and C I) originate in low-temperature icy condensates, their presence implies that heating has not been systematically $>$120 K. They may also be produced by the dissociation of CHON particles. Regardless of the origin of the N I, the presence of He I (Grinin et al. 1994; 1996) in a number of HAeBe star spectra is consistent with release of helium trapped in icy clathrate structures. The suggestion that the silicates in the parent bodies are preferentially Mg-rich, together with the presence of large amounts of carbon originating in a refractory parent, is also consistent with predictions for the composition of comets (Greenberg 1998) and with data on Solar System comets such as P/Halley and C/Hale-Bopp. We conclude, therefore, that the infall signatures reflect the presence of high levels of star-grazing cometary activity.

IV. DYNAMICS OF THE INFALLING MATERIAL

The infalling material is routinely observed with velocities nearing the free-fall velocity (100s of km s^{-1}). In contrast, other grain acceleration mechanisms produce velocities orders of magnitude smaller, e.g. Poynting- Robertson drag (10s of m s^{-1}), the behavior of small grains in the presence of gas drag, or infall from a larger, extended envelope ($v \leq 1$ km s^{-1}).

As a consequence of the strong radiation fields of these stars, grains which are smaller than several microns are subject to radiation pressure-driven outflow (Sitko et al. 1994) rather than infall. The presence of grains which are smaller than the blow-out radius, would therefore imply a replenishment mechanism, since under equilibrium conditions such grains are expected to be removed from the immediate vicinity of the star, and thus not contribute appreciably to the polarization, or IR emission spectrum of the inner disk. Sub-micron grains in the disks of HAeBe stars are manifested via their optical (Grinin et al. 1991) and UV (Bjorkman et al. 1995) polarization characteristics, and via the presence, in some systems of mild UV-excesses consistent with dust-scattered light. The most dramatic signatures of such grains are the IR emission features due to small grains (see §V, below). Particularly for the UXORS, where the inner disks are apparently quite inhomogeneous, such grains are likely to be a byproduct of the cometary activity producing the infall signatures.

The velocity data imply that the solid bodies associated with the gas features are sufficiently large to maintain free-fall velocities until they disintegrate (Grinin et al. 1994; Sorelli et al. 1996), providing a lower bound to the size of the parent bodies. An upper bound to the size of the parent bodies is provided by the composition of the infalling material. The mixture of low temperature condensate dissociation products, super-refractory grains, silicates, and intermediate temperature materials suggests the presence of parent bodies which, while sufficiently large to achieve substantial fractions of the free-fall velocity, are not so large that density differentiation has occurred and/or that insufficient time has elapsed for any such effect. The observed non-equilibrium mixture of materials is consistent with cometary composition and meets our expectations for planetesimals.

V. THE SMALL GRAIN COMPONENT OF THE DISKS

UV-IR spectra of HAeBe star disks provide ample evidence for the presence of small grains in the immediate vicinity of the star. A number of the nearest HAeBe stars lack associated reflection nebulosity and/or provide no indication of extensive envelopes (Henning et al. 1998). ISO data have greatly augmented the sample of stars with PAH and UIR band detections, but indicate that for these stars the band features do not provide the bulk of the 2-8μm IR emission (Waelkens et al. 1996; Waters & Waelkens 1998; van den Ancker et al. 1999). Moreover, not all HAeBe stars exhibit PAH features (van den Ancker et al. 1999).

The more extensive silicate data can also provide additional constraints on the location of some of the small grains. Silicate emission bands are routinely detected in the spectra of a number of HAeBe stars, and have been spectacularly revealed by the ISO SWS (Waelkens et al. 1996; van den Ancker et al. 1999), where in some cases the optically thin emission dominates the IR excess of the star shortward of 60 μm. The SWS data however, lack spatial resolution on a scale comparable to the size of the disks inferred from the mm-data. Ground-based IR measurements of the 9.5 μm Si-O band show that such features are routinely detected in small aperture (e.g. 3.4$''$ diameter hole used by the BASS at the IRTF), corresponding to a radial distance r$\leq$200 AU for stars, such as HD 163296, at distances of 120 pc. Widening the aperture (to 11$''$, Sitko 1981b) does not increase the detected flux or change the silicate features, implying that the bulk of the silicate emission is located within 200 AU of the star. In addition, the continuum fluxes in the disks resolved with millimeter-wavelength interferometry are the same as those derived from single-dish measurements (Natta et al., this volume), indicating that the dust emission is not coming from extended material around these stars.

Model fits to the ISO IR emission spectra of several of the nearest HAeBe stars are consistent with optically thin, warm (T=210 K) silicate grains (Malfait et al. 1998; van den Ancker et al. 1999). Such warm grains must be comparatively near the star, and thus provide a probe of the solid state material in the *innermost portions of the disk*. In particular, grains which are below the radiation-pressure blowout radius require replenishment on time scales which are short compared to the PMS evolution of stars. These transient grains hold the key to understanding the mineralogical composition of the dust, which gives rise to the infalling gas signatures that are observed.

A. Size Distribution

Extinction by dust in the HAeBe stars is unlike that of the general interstellar medium. This difference is due to the fact that the mean grain size is considerably larger in these disks than in interstellar dust

(Sitko et al. 1981a; Sitko et al. 1984; Sitko et al. 1994). This difference in grain size affects the strength and shape of the 10μm silicate band. Small optically-thin grains produce a strong emission feature, while big optically thick (in the continuum) grains do not. Interstellar grains (with a large component of small particles) are observed to produce an emission band with a band/continuum ratio of about 3, as in the Trapezium. The same feature seen in solar system comets has a smaller ratio, usually less than 2 (Hanner et al. 1994), while that observed in the zodiacal light of the solar system has a ratio of about 1.15 (Reach et al. 1996). Such a trend toward a smaller ratio is expected as the spectrum becomes dominated by larger and larger particles. Smaller grains are removed by radiation pressure from the star, while larger ones are not.

The majority of HAeBes observed so far have band/continuum ratios intermediate between those of Trapezium-like and solar system zodiacal dust, and are similar to those of comet comae. Due to the large ratio of luminosity to mass in the HAeBe stars, small grains (less than a few μm in size) are easily removed by radiation pressure on time scales of centuries. The fact that we see a large silicate emission band while grain blowout is so efficient indicates that the small grains must be replenished on similar time scales by the erosion of larger bodies that were presumably built at an earlier epoch. This is consistent with the grains coming from cometary objects in the HAeBe stars.

B. Mineralogical Composition

The IR spectra of the stars showing cometary activity contain a wealth of information concerning the mineralogical composition of the refractory and volatile solids that are present and which are presumably the source of the high-velocity gas. The solids detected fall into three broad classes: refractory inorganics, refractory organics, and ice.

Mineralogy of the Silicates

These catagories are also representative of the material in solar system comets and (except for ice) are present in interplanetary dust particles (IDPs) of (presumed) cometary origin. The most ubiquitous spectral feature seen in these stars is the 10 μm emission band due primarily to silicate materials (Waelkens et al. 1996; van den Ancker et al. 1999; Butner et al. 1998; Malfait et al. 1998a). The same feature is also present in solar system comets (Fig. 5). By comparing the spectral structure observed in these objects with those of materials prepared in the laboratory (for example Stephens & Russell 1979; Stephens et al. 1995; Jager et al. 1994; Dorschner et al. 1995; Henning et al. 1995; Hallenbeck et al. 1998), and with anhydrous chondritic interplanetary dust particles (IDPs) of known mineralogy (Sanford & Walker 1985, Bradley et al. 1992) it is possible to identify the features seen in the stellar spectra with general mineralogical classes. This emission band is consistent with a mixture of silicate material composed primarily of pyroxenes - (Mg,Fe,Ca)SiO_3 - and olivine - $(Mg,Fe)_2SiO_4$. The long-wavelength wing of this band, with a local maximum near 11.2 μm, is due to crystalline olivine (Fig. 5.). When spectral information longward of 14 μm is included, the identification can be made even more specific. In HD 100546 (the Rosetta Stone of HAeBe IR spectra), the data indicate that the crystalline olivine is forsterite - Mg_2SiO_4 (Sitko et al. 1996; Waelkens & Waters 1996; Malfait et al. 1998a; Sitko et al. 1999).

Even stronger in the majority of the 10 μm bands in HAeBes than the olivine feature is another feature that peaks near 9.5 μm (Fig. 6). In laboratory-produced silicates, IDPs, and in C/Hale-Bopp (Wooden et al. 1998) this feature is due to pyroxenes, with enstatite - $MgSiO_3$ being a likely candidate. The time-of-flight impact-ionization mass spectrometers on the Giotto (PIA) and Vega (PUMA) Comet Halley probes found that the silicates in Halley were Mg-rich and Fe-poor (Jessberger & Kissell 1991; Schulze et al. 1997 and sources therein). Also, detailed chemical analysis of IDPs with comet-like (HAeBe-like) spectral features indicate that most of the Mg is tied-up in silicates (Bradley et al. 1992). Thus, the silicates in both HAeBes and comets are Mg-rich, and that is where most of the Mg resides.

Crystallinity of the Silicates

The crystallinity of the olivine in the spectra of β Pic, HAeBe stars, and solar sytem comets is perplexing, because it is not seen in the interstellar medium grains from which these objects formed. Where is it made? Annealing of amorphous pre-solar grains in the inner protostellar nebula (or condensing them there directly from the gas), transporting them to the region where comet formation is occuring, and then mixing them with ice grains that probably condensed only at temperatures $\leq$30 K (Crovisier et al. 1997) appears to be required. The mechanism for producing such mixing is not well-understood, but a similar mechanism is also required to explain the degree of deuterated water in Comet Hyakutake (Bockelée-Morvan et al. 1998). This difficulty is analogous to that of getting melted silicates, i.e. chondrules, into the volatile-rich material which eventually gave us the carbonaceous chondrites. Many models have been suggested; none are without difficulties (Hewins 1997).

Iron

The IR spectra of HAeBes, chemical analysis of the "cometary" IDPs, and mass spectrometer data on Halley indicate that Fe is not exclusively tied up in silicates, but occurs in significant abundance in a variety of other materials. In the case of both Halley dust (Schulze et al. 1997) and the "cometary" IDPs, Fe is primarily present as metal (kamacite), oxides (magnetite), and sulfides (see Bradley et al. 1992). Fe-rich oxides (but not silicates) are also consistent with the IR spectra of HD 100546 (Malfait et al. 1998a), HD 163296 and AB Aur (van den Ancker et al. 1999) and with the UV data.

Refractory Organics

The spectra of some HAeBes have emission features located at 3.28, 6.2, 7.7, 8.6, and 11.3 μm, which are indicative of organic materials. Sometimes additional bands at 3.4 and 3.5 μm are also present. The most popular explanation of these features are that they arise from vibrational transitions in Polycyclic Aromatic Hydrocarbons (PAHs), a refractory organic material that can range in size from a dozen atoms (like benzene) to molecules so large that we might consider them to be small grains. Other related organics, such as Hydrogenated Amorphous Carbon (HAC) and quenched Carbonaceous Composites (QCC) have also been suggested. Among those HAeBes with infalling gas, HD 100546 stands out with very strong organic features. In another HAeBe, HD 97048 (not known to have infalling gas at the present time), speckle observations of the 3.5 μm band indicate that the emitters are located within 8 AU of the star (Roche 1986).

Comets contain a significant component of refractory organic material. In Halley dust, a significant fraction of the refractory material is organic, composed of a mixture of C, H, O, and N ("CHON"). Cluster analysis of the PUMA-1 and PUMA-2 data indicates the presence of pure carbon, hydrocarbons and polymers of cyanopolyynes, and multicarbon monoxides (Fomenkova et al. 1994). In the IDPs, the refractory organic material is present as metal (FeNi) carbide and graphitic carbon as well as a disordered carbonaceous matrix (Bradley 1994). This carbonaceous matrix also contains N with an N/C ratio of about 0.1, i.e. chondritic (Keller et al. 1996). The CHON material may thus be one of the most important sources of N seen in the infalling gas. This CHON material is probably the source of most of the atomic and ionic C and N observed in the UV spectra of the accreting gas in these systems, and may be related to the organic emission features seen in the IR of the HAeBe stars. It is important to note that the ubiquitous IR bands seen in the HAeBe stars and the interstellar medium are weak (or absent) in solar system comets. The 6.2, 7.7, 8.6, and 11.3 μm bands that are so apparent in the ISO spectrum of HD 100546 are not visible in the spectrum of Comet Hale-Bopp (see Fig. 5 of Malfait et al. 1998a). Nor is the 3.3 μm band seen in the ISO spectrum of Hale-Bopp (Crovisier et al. 1997). While the 3.2-3.6 μm region of comets does possess an emission band, it seems to be dominated by methanol and the 3.4 μm emitter (whatever its nature), with the 3.3 μm band being the weakest, if present at all (Fig. 3 of Bockelée-Morvan et al.

1995). Joblin et al. (1997) have estimated the lifetimes of gas-phase neutral PAHs at 1 AU from the sun to be on the order of only 15 seconds. PAHs are, however, found in organic-rich meteorites, along with fullerenes and fulleranes (Becker and Bunch 1997). The chemical processing of organics in both the protosolar nebula and larger condensed bodies is a ripe field for further investigation.

Ices

Finally, we know that ≈50% of the mass of comets is in the form of water ice (which does not survive in captured IDPs), and ought to be present in the dust in accreting-gas HAeBes. While the high temperatures and small optical depths make observing the 3.1 μm ice absorption band difficult in these stars, the HD 100546 ISO data for $50 \leq \lambda \leq 80$ μm are consistent with emission by cold ice (Malfait et al. 1998a). The ice may also be a reservoir for trapped volatile gases in clathrate hydrates.

The evaporation of cometary materials from parent bodies on highly eccentric orbits towards HAeBe stars will naturally give rise to the observed, redshifted absorption features, partial covering factors, and wide range of observed atomic ions.

VI. IMPLICATIONS

Both the infalling circumstellar gas and the small dust grains which can be remotely sensed around young, intermediate-mass stars bear a close resemblance to cometary materials in our own Solar System (see Table 2). Dynamically, the closest analog to the infalling bodies are the Kreutz family of Sun-grazers which not only have their eccentricities pumped up by encounters with Jupiter, but also exhibit rich emission spectra from refractory elements (see Table 1).

Infalling circumstellar gas, similar to β Pic's, is routinely detected in the PMS (HAeBe) and young main sequence (Shell-Star) systems viewed within ≈14° of their disk mid-planes. This limit is consistent with recent determinations, from imaging of the disk, of the system inclination for HR 4796 (Koerner et al. 1998) and Fomalhaut (Holland et al. 1998). Infall detections are routine among the 1-4 Myr old systems, but show signs of transitioning to more episodic infall between 6 (HD 163296) and 10 Myr (HD 100546), similar to that reported for β Pic (Deleuil et al. 1995) (Fig. 7). There are only more sporadic detections of infalling material in the lines of sight to older, dated systems, with one detection toward the primary of a Lindroos (1986) double at t=79Myr, and infalling material present in the UV spectrum of Pleione (t≈100 Myr). There are some suggestions that close binaries make the transition to main sequence star levels of cometary activity earlier than the isolated systems, with low levels of infall present in 51

Oph (t=0.3 Myr, van den Ancker et al. 1997), and HD 176386 (t=2 Myr, Wilking et al. 1985; Grady et al. 1993).

Models for the β Pic system suggest that both long-term fluctuations in the infall rate and the presence of preferred velocities for the star-grazing cometesimals are signatures of perturbations on the disk by one or more Jupiter-mass planets (Deleuil et al. 1995; Beust et al. 1996). The HAe star data suggest that episodic infall, together with the development of prominent mid-IR "gaps" in the IR spectral energy distributions (Malfait et al. 1998b) become macroscopically detectable by 10 Myr (HD 100546). If multi-year fluctuations in the frequency of optical minima in younger HAe stars with UXOR light variations (Schevchenko et al. 1993a,b; Schevchenko & Herbst 1998; Grinin et al. 1998) represent similar activity, the effects of large bodies on the disk become detectable by 1-4 Myr in systems with no known close *stellar* companions. These observational contraints are broadly consistent with theoretical estimates of the time needed to produce a Jupiter (Pollack et al. 1996), and are consistent with identification of TMR-1C as a planet (Terebey et al. 1998).

Studies of the circumstellar material around intermediate- mass stars have greatly benefitted from access to data from the FUV through the far-IR. We anticipate that more detailed studies of many of these objects will continue with current and new instrumentation and will begin to give us a full view of the dynamics of these systems as forming planetary systems. However, infall activity and the related signatures of larger bodies within circumstellar disks do not appear limited to intermediate mass stars. Several weak-line T Tauri stars have been identified with large amplitude polarimetric and photometric variability similar to that observed toward suitably oriented, young HAeBe stars (Gahm et al. 1993; Alcalá et al. 1993; Guenther & Hessman 1993; Grinin et al. 1995). These stars have evolutionary ages spanning $3 \leq t \leq 10$ Myr (Gahm et al. 1993; van den Ancker et al. 1998a), making them contemporaries of the HAeBe systems. Comparatively weak optical emission features, and IR excesses indicative of central clearing of the disks (Alcalá et al. 1993) argue against gas-phase accretion from a classical accretion disk in these systems. However, these objects exhibit prominent infall signatures in transitions such as Hα and Na I D. The available data for these stars suggests that we are seeing β Pic-like cometary activity in the disks of these stars. The presence of cometary activity in one system with an age of $\geq$10 Myr suggests that high rates of cometary bombardment continue for longer times around these isolated, young Suns than for the HAeBe stars. The presence of such activity has important implications for the potential delivery of volatiles to terrestrial planet cores in such a disk, and thus potentially to the development of life-bearing worlds. We anticipate that detailed studies of these objects will be as pivotal to studies of planetary system evolution in the next decade as β Pictoris has proven to be in studies of intermediate-mass stars. Exciting times lie ahead.

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TABLES

Table 1. Comparison of Sun-grazing comet properties, (based on 2 years of observation by SOHO/LASCO, Biesecker 1998, priv. comm.) with the line of sight (LOS) infall events in HAeBe and MS disks.

Table 2. Summary of Herbig Ae/Be Star Properties.

FIGURES

Figure 1. Infalling, circumstellar gas profiles for HD 100546 at two epochs: 7 March 1995 (high infall state, bold) and 25 May 1995 (thin line). Infalling gas is seen over a wide range of ionization stages, ranging from neutral atomic gas species such as O I and N I, through intermediate ionization stages such as Si II, and including species which are produced by collisional ionization in the radiation field of the B9 star, such as C IV.

Figure 2. Infalling gas is routinely observed in multiple ionization stages of the same element. In the case of HD 100546 and other HAeBe stars, neutral atomic gas may be restricted to the infalling material. Collisionally ionized species, such as C IV may also be preferentially observed in the infalling gas. Here C I (4) (thick,bold) and C IV (thin line) in HD 100546 from 1995 March 7 are shown with C II (dot-dash) in the same spectrum. The zero-point of the radial velocity scale corresponds to the laboratory wavelength for the shorter wavelength component of the C IV resonance doublet, the longer wavelength member of the C II doublet, and the transition to the O eV level of the ground configuration in C I (4).

Figure 3. Schematic display of the elements detected *in the infalling gas*, ordered by gas phase sublimation temperature (after Jenkins 1987), toward some of the nearest Herbig Ae/Be stars with the most complete wavelength coverage and β Pic. Filled symbols indicate firmly detected elements, with the small symbols indicating the elements which have anomalously weak covering factors. Open symbols indicate elemental non-detections. Gaps indicate elements lacking suitable data coverage. Several of the stars (e.g. HD 163296 and AB Aur) have emission in H I, He I, and Na I (AB Aur). With the exception of HR 5999, the displayed stars lack nearby stellar companions. The stars are ordered roughly from bottom to top in terms of increasing system age.

Figure 4. Dynamic spectral image of the Mg II resonance doublet in the Herbig Ae star AB Aur, from a dense time series obtained by IUE in 1990 (from Pérez and Grady, 1997). Time increases upward and wavelength increases to the right. The spectral data have been normalized by the mean spectrum (shown at the bottom of the figure). Gaps in data coverage are denoted by black horizontal bands. The dark absorption in both members of the Mg II resonance doublet are due to saturated absorption in the stellar wind, which is typically observed in spectra of this star. During the time series, enhanced absorption redward of line center developed to the right of each of the Mg II emission components, beginning halfway through the series and continuing until the end of the observations.

Figure 5. Continuum normalized, and continuum subtracted 10μm silicate profiles of a range of HAeBe stars (left), laboratory silicates (center), and comets (right). The astronomical data were normalized to a local continuum fit as a gray body at 8.5 and 12.3 μm. The most prominent emission, peaking at 9.5 μm, is seen in young (t$\approx$1 Myr) systems such as UX Ori. Intermediate emission levels are seen in BF Ori (2-3 Myr), AB Aur (4 Myr), HD 163296 ($4^{+6}_{-2.5}$ Myr), with the most prominent feature at 11.2 μm in HD 100546 (>10 Myr, dark, bold). The central panel shows laboratory Mg-silicate smokes which have been annealed 2 and 7 hours at 1030 K (Hallenbeck and Nuth 1998, priv.comm.). The right panel shows silicate emission features from Solar System comets Wilson, Borrelly, Levy, Bradfield, and Halley (bold, dark).

Figure 6. The spectrum of HD 163296 compared to a model comprised of glassy enstatite (small dash), glassy olivine (dot-dot-dash), crystalline olivine (large dash), and an underlying blackbody continuum component (solid line), all at T=440K from Sitko et al. (1999).

Figure 7. The evolutionary interval over which high covering factor infall is detectable in UV/optical spectra of young, intermediate-mass stars spans the age range from the point that the stars become directly observable at $\approx$0.1Myr with Lada (1987) class II IR excesses to the point at which the IR excess resembles that of Vega. The frequency of infall detections ramps down rapidly from 3-4 Myr to the age of β Pic. Infalling gas and material at the system velocity have not been reported for stars older than 200 Myr (Lecavelier des Etangs et al. 1997). Similarly, dust detections become increasingly scarce for stars in this age range (Abraham et al. 1998).

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