The Nearest Pre-Main Sequence Multiple Stars

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Summary. Protoplanetary disks are where planets form, and where the pre-biotic materials which produce life-bearing worlds are assembled or produced. We need to understand them, how they interact with their central stars, and their evolution both to reconstruct the Solar System's history, and to account for the observed diversity of exo-planetary systems. Our knowledge of these systems, in terms of their disks, gas content, dust mineralogy, and accretion is most complete for the nearby PMS A stars, the Herbig Ae stars. Previously, many of the nearby Herbig Ae stars were thought to be single stars: a new generation of high angular resolution and high contrast imagery has revealed a number of binary, and multiple star systems, with a wide range of signatures of dynamical interaction with the primary star. Our current understanding of these systems is reviewed.

1 Introduction

The first 20-30 Myr in the evolution of a planetary system appear to be crucial in establishing the architecture of the system. The nearest debris disks in the β Pictoris moving group, β Pic and AU Mic at 12 Myr have centrally cleared debris disks with dynamical signatures of the presence of as yet unseen planetary mass bodies (Wahhaj et al. 2003 [50]; Liu et al. 2004 [30]), and no protoplanetary disks older than ≈ 10 Myr are currently known. In our own Solar System, the meteoritic and impact data indicate that the first 20-30 Myr spans the era of planetesimal formation, central clearing of the inner disk, and the formation of the terrestrial planet embryos (Jacobsen & Yin 2003 [24]; Kleine et al. 2003 [26]).

The PMS and young planetary systems which are currently easiest to study are nearby systems with large disks which are well-illuminated by their central stars, favoring systems around stars which are more massive, and hence luminous than the Sun. Similarly, prior to the launch of *Spitzer*, our knowledge of the dust mineralogy of the inner disks was far more complete for disks associated with A stars than for young, Solar analogs. Line of sight absorption studies also favor A and B stars since these rely, particularly at UV and FUV wavelenghts where many of the atomic and ionic transitions of cosmically abundant elements are concentrated, on the availability of a bright, rotationally washed-out, photospheric spectrum as a background continuum. The result is that currently we know the most about protoplanetary and debris disks associated with 1.5-2.5 $M_\odot$ stars within 150 pc of the Sun.

2 Finding the Binary and Multiple Systems associated with the A Stars

While our knowledge of the disks, dust mineralogy, and the circumstellar gas is most complete for young, nearby, lightly reddened A stars, our knowledge of whether these objects are single or multiple systems is much less complete than either for low-mass stars, where the presence of even planetary mass companions can be easily detected from the ground (Chauvin et al. 2005 [9]), or for bright, massive stars which provide abundant photons for bispeckle analysis or for interferometry. In the optical, these stars are typically bright, with 8.5≤V≤3.1. The immediate consequence is that in conventional, broad-band optical surveys such as the DSS, or even the Supercosmos Hα survey, the light of the A star swamps a region between 5-30" from the star (Fig. 1). Near-IR surveys, such as 2MASS are a bit better since the contrast between a late-type star and the A star is more favorable, but are typically unable to detect stellar sources closer than 5" from the primary. Moving to wavelengths where late-type stars are still conspicuous, and older A stars are not observed to be bright, such as in the x-ray (Simon et al. 1995 [40] has proven to be a more promising technique. X-ray surveys such as the ROSAT All-Sky Survey (RASS) were sufficiently deep to detect single, low-mass stars out to 50 pc, and multiple systems at larger distances, while deeper, pointed observations can sample the entire region within 150 pc of the Sun, albeit at low spatial resolution (≈15"). Such surveys have revealed a hitherto unexpected wealth of young stellar associations and moving groups (see review by Zuckerman & Song 2004 [59]) which are securely dated to 5-50 Myr. Deeper, and higher resolution imagery, such as can be provided by *Chandra* are needed to sample activity from brown dwarfs in this age range (Tsuboi et al. 2003 [47]).

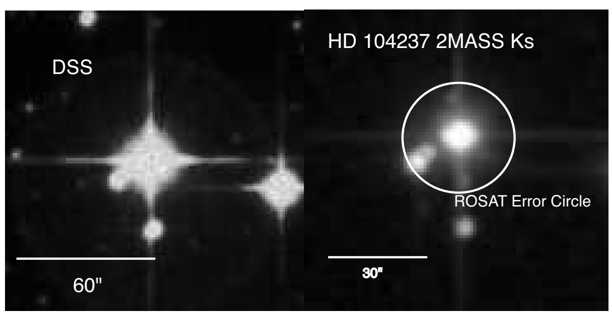

Fig. 1. Optically bright Herbig Ae stars present a challenging environment for the detection of low-mass stellar companions. Left: In the DSS, light from HD 104237 swamps the region within 12" of the star, with only one companion visible. Right: At Ks, as seen by 2MASS, the 15" and 10" companions are visible.

Both the HR 4796 A/B/C and HD 141569 A/B/C (Weinberger et al. 1999 [53], 2000 citeWeinb00) systems were detected in the RASS (de la Reza & Pinzón 2004 [12]). Higher angular resolution *Chandra* imagery of HD 141569 (Feigelson et al. 2003 [15]) indicates that 2 of the 3 expected sources were detected, with L_x in the range expected for young M stars. Feigelson et al. (2003) [15] identify these sources with the A star and an unknown companion, but Stelzer (2005, priv. comm.) notes that the x-ray sources are more correctly associated with the 2 M stars. Similarly, archival *Chandra* imagery containing HR 4796 A detects the M stars, but not the A star, providing an upper limit to the x-ray luminosity of the A star of 10^{26} erg s^{-1}, some 3 orders of magnitude below the level typical of accreting Herbig Ae stars (Hamaguchi et al. 2005 [23]).

The disks in these systems indicate the presence of sculpting by the companions. HD 141569 A has distinct rings in the scattered light imagery of the disk, and tidal tails reminiscent of interacting galaxies extend to the M star companions (Clampin et al. 2003 [11]; Mouillet et al. 2001 [33]; Augereau et al. 2001 [3]). Some of the structure in the HD 141569 A disk has been linked to the M-star companions (Augereau & Papaloizou et al. 2004 [4]). HR 4796 A's disk is a distinct ring at 70 AU (Augereau et al. 1999 [2]; Schneider et al. 1999 [38]; Koerner et al. 1998 [27]; Jayawardhana et al. 1998 [25]) consistent with truncation of the disk by the companions. No tails are visible in the HR 4796 system, but Ardila et al. (2005) [1] note that such features should be ephemeral. In both cases there appears to be central clearing of the disks, which has prompted speculation that there are additional, potentially planetary mass bodies in the inner disk (Wyatt et al. 1999 [57]; Ardila et al. 2005 [1]).

Single A stars at d=100 pc are below the RASS detection limit, but multiple systems are still detectable, and deeper, pointed observations can reach 10^{29} erg s^{-1} (Hamaguchi et al. 2005 [23]; Zinnecker & Preibisch 1994 [58]). *Chandra*, with its greater sensitivity and 1" resolution, can reach upper limits of $L_x=10^{26}$ erg s^{-1}, a factor of 100 below the RASS upper limits for nearby associations. *Chandra* has demonstrated that younger, and actively accreting A stars do indeed appear to be x-ray sources, or to have x-ray sources associated with the A star at the 1" resolution of *Chandra* (Feigelson et al. 2003 [15], Skinner et al. 2004 [42]; Swartz et al. 2005 [45]). These x-ray detections include the optically brightest Herbig Ae star, DX Cha (HD 104237).

3 HD 104237

Long considered the prototype for an "isolated" Herbig Ae star, HD 104237 (d=115 pc, van den Ancker et al. 1997 [49]) is among the few Herbig Ae stars detected in the RASS, and is sufficiently bright and hard to permit higher energy x-ray observations with ASCA (Skinner & Yamaguchi et al. 1996 [41]). *Chandra* not only detected a source coincident with the A star, but a string of sources spanning 20" (Feigelson et al. 2003 [15]; Skinner et al. 2004 [42]; Fig. 2). Subsequent optical and IR imagery reveal the presence of 3 T Tauri stars at 1.2-15" from the A star, two of which have IR excesses in their own right. The hottest member of the association, an extremely late A star, or early F star with UV excess, is actively accreting, and drives a bipolar microjet (Grady et al. 2004 [19]). Subsequently, Böhm et al. (2004) [6] find that this object is itself a spectroscopic binary, with the companion a likely K star.

The disk around the Herbig Ae star is not directly detected in HST coronagraphic imagery, although thermal emission and solid-state features are conspicuous in mid-IR spectroscopy (Meeus et al. 2001 [32]; van Boekel et al. 2005 [48]). An

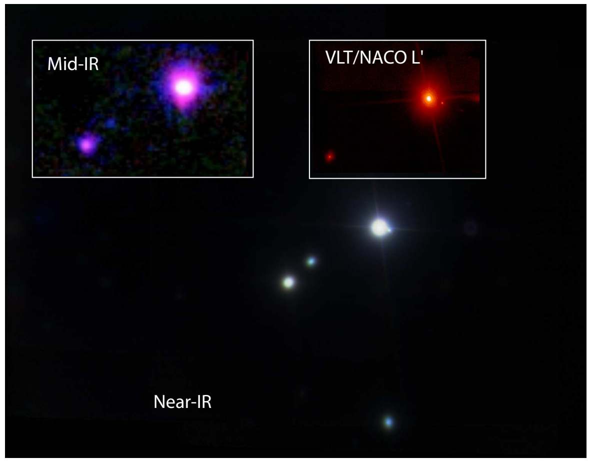

Fig. 2. The optically brightest Herbig Ae star, HD 104237, is revealed as the brightest member of a small aggregate of T Tauri stars. The presence of a circumstellar excess is visible in a color-composite image (J-H-K) made with the VLT/NACO while the presence of mid-IR excesses can be seen with two of the T Tauri companions at L′ (upper right) and L′-M-N (ESO 3.6m and TIMMI II (upper left).

upper limit to the disk size is provided by the closest point where the counterjet, which is seen in projection behind the disk, can be detected. For HD 104237, this is 0.6” (70 AU). The disk non-detection from the HST/STIS coronagraph suggests that the disk is somewhat smaller, with r≤0.5” (58 AU). The disk size limit is somewhat larger than the 0.3 × the projected separation between HD 104237 A and B, suggesting that the projected separation of the two stars is a lower bound to the true separation.

4 HD 169142

First identified as a Vega-like system in the late 1980s (Walker & Wolstencroft 1988 [51]), HD 169142 differs from typical debris disk systems in having a conspicuous PAH emission spectrum (Sylvester et al. 1996 [46]; Meeus et al. 2001 [32]). Molecular gas is present in the disk, with CO at a level intermediate between debris disks and the accreting Herbig Ae stars (Dent et al. 2005 [13]). The disk has been imaged via differential polarimetric imaging (Kuhn et al. 2001 [28]) at H, coronagraphically from the ground at Ks (Boccaletti et al. 2004 [5]), and at F110W with HST/NICMOS. In all cases the disk presents as face-on nebulosity (i≤20°) with a surface brightness intermediate between bright nebulosity such as that seen in HD 141569 (Weinberger et al. 1999 [53]; Augereau et al. 2001 [3]; Clampin et al. 2003 [11]) and fainter disks like HD 163296 (Grady et al. 2000 [17]). While Kuhn et al. (2001) [28] report patchy structure in the disk, there is no hint of such features in the NICMOS imagery; instead the disk presents as a featureless structure out to 1.1” from the star with surface brightness dropping slowly with increasing distance from the star. The PAH emission seen by Sylvester et al. (1996) and Meeus et al. (2001) [32], is spatially extended to at least 0.2” from the star (20 AU) (Habart et al. 2005 [22]). In combination with the appearance of the IR spectral energy distribution (SED), these data all indicate the presence of a flared disk with a flare angle which is intermediate between systems like HD 100546 (Grady et al. 2001 [18]; 2005a [20]) and geometrically flat systems like HD 163296.

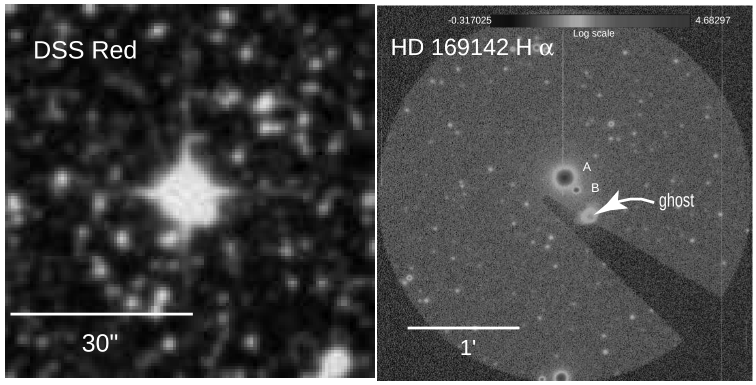

Fig. 3. While the presence of an 8” companion to HD 169142 is at best marginally resolved in DSS red imagery, both stars are conspicuous in narrow-band imagery obtained with the Goddard Fabry-Perot on the Apache Point Observatory 3.5m.

A ROSAT source (2RXP J182429.1 -294659) is located within 14” of the Herbig Ae star. At the spatial resolution and positional accuracy of ROSAT, this source has a high probability of being associated with the Herbig Ae star. However, at d=145 pc, the A star alone cannot account for the x-ray emission. When scaled to a count rate at d=115 pc, the observed count rate of 0.0645 c/s is comparable to that of the HD 104237 aggregate, and is consistent with the presence of 3-5 objects similar to those seen in the HD 104237 aggregate. 2MASS imagery reveals a source 7-8” to the SW of the Herbig Ae star (Fig. 3) which partially confused with the Herbig Ae star. Higher angular resolution data obtained with the Goddard Fabry-Perot on the Apache Point Observatory 3.5m demonstrates the presence of Hα sources at the Herbig Ae star and at the 7.7” object. Low resolution spectra obtained with the Apache Point observatory Dual Imaging Spectrograph indicate a type of M2.5Ve for the 7.7” source (Fig. 4). This object has apparently been co-moving with the Herbig Ae star since the mid-80s, excluding a foreground Main Sequence M star. Second epoch high angular resolution imagery will be needed to demonstrate that the 7.7” object shares the proper motion of the Herbig Ae star against the numerous background stars, but, as noted for HD 141569 A, the probability of finding a T Tauri star and a Herbig Ae star in this proximity at this distance and having them not associated is neglibly small.

Is this the only nearby late-type object which can be associated with the Herbig Ae star? Detection of point sources near brighter objects is facilitated in NICMOS imagery by differencing data obtained at two spacecraft roll angles, such as are routinely obtained for all NICMOS coronagraphic observations (Lowrance et al.

2000 [31]). When applied to HD 169142, the 7.7" object is seen in both images (Fig. 5). There are numerous fainter objects in the NICMOS imagery, but none are seen closer than 2" to the Herbig Ae primary. However, careful inspection of the NICMOS data further reveals that the 7.7" source is resolved into a 112 mas pair, with a 0.7 magnitude difference at F110W (Fig. 6). Tiny-Tim fits to the two sources do not account for all of the NIR light, suggesting that there is either a third source in the vicinity of the M stars (associated or background) or circumstellar material. Combining the NICMOS data, converted to J, an assumed distance of 145 pc, and a stellar T_{eff} consistent with the optical spectrum yields an estimated age for the M stars of 8±2-3 Myr.

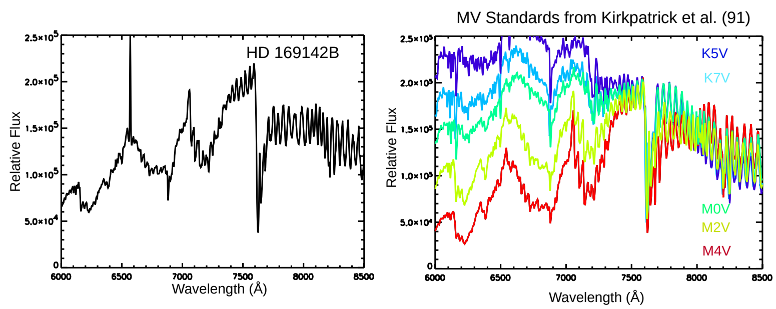

Fig. 4. The 8" source has both the Hα emission and an M2.5V spectral type expected for a young, late-type companion to a Herbig Ae star, as seen in low resolution spectra obtained with the Apache Point Observatory 3.5 m and Dual Imaging Spectrograph.

Central Clearing of the Disk: Clearing the center of the disk is an expected consequence of planetary system formation, but can also mark the dynamical effects of a stellar or substellar companion (Augereau & Papaloizou 2004 [4]) or an encounter with an unbound companion (Quillen et al. 2005 [35]). The low fractional IR luminosity of this system (0.08, Dunkin et al. 1997 [14]), and deficit of thermal emission from warm grains, detectable either as an excess at $\lambda \leq 8$ μm, or as emission in the 10μm silicate band suggested a deficit of small grains near the star. While the star does exhibit emission lines indicative of the presence of stellar activity, such as the Hα and He I emission noted by Dunkin et al. (1997) [14], and the Lyα, O I, C II and C IV seen in IUE spectra, the star does not exhibit any detectable UV excess longward of 1600 Å when compared to UV spectral type standard stars. This is in marked contrast to the actively accreting Herbig Ae stars such as MWC 480 (Stecklum et al. 2005 [44]), HD 163296, and HD 104237 (Grady et al. 2004 [19]), all of which have distinct excess light at these wavelengths. Moreover, narrow band Hα observations do not reveal any HH knots such as are seen in GFP data for HD 163296 (Wassell et al. 2005 [52]). This suggests a deficit of gas in the immediate vicinity of the Herbig Ae star. Habart et al. (2005) [22] have resolved the 3.3μ PAH emission in HD 169142. After a rapid increase in strength with decreasing radius from the star in to ≈25 AU, the PAH emission profile flattens out at smaller radii. The mid-IR PAH features are transiently excited by the absorption of a FUV pho-

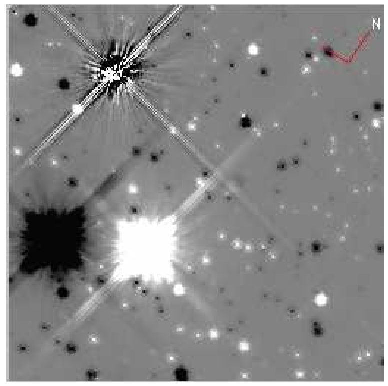

Fig. 5. Roll-differenced HST imagery affords an efficient way of removing the stellar point spread function and any circularly-symmetric nebulosity (e.g. face-on disks), to reveal point sources in the immediate vicinity. NICMOS coronagraphic imagery is sufficiently deep to detect J=19.5 sources within a few arcseconds of the occulted primary. Associated, stellar companions have conspicuous diffraction spikes, while brown dwarfs and background objects can be significantly fainter. The NICMOS data provide no indication of a companion within 0.3≤r≤2" of HD 169142.

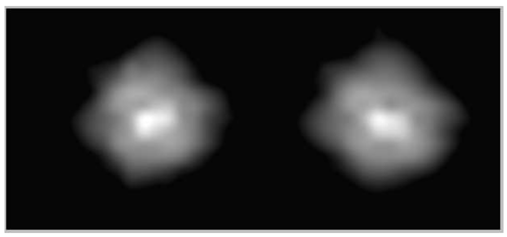

Fig. 6. The 7.7" companion to HD 169142 is resoved by HST/NICMOS into two sources, seen here at two different spacecraft roll angles.

ton, which in this system would be most likely a Lyα photon, and should exhibit an r^{-2} dependence for a constant number density of PAHs with radius. A roll-over in the profile is similar to the behavior of the fluorescent H_2 emission in HD 100546 (Grady et al. 2005a [20]). The combination of a deficit of PAH emission near the star, the absence of warm dust features, and the low current accretion rate, all indicate the probable presence of an additional body in the inner portion of this disk. Follow-on HST/ACS and *Chandra* imaging may prove useful in establishing the nature of any such close companion, however, given the estimated age, a planetary mass companion cannot be excluded.

5 Binarity and Multiplicity

Not all of the optically visible, bright Herbig Ae stars are members of multiple systems or single stars. The HST coronagraphic surveys of Herbig Ae stars were initially selected based on the presence of an optically detected star with minimal foreground extinction and overall proximity to us. The STIS sample included only two binary/multiple systems, HR 5999 and the HD 104237 aggregate (Grady et al. 2005b[21]). NICMOS coronagraphic imagery is now available for additional Herbig Ae stars with low-mass companions, including HD 169142 and HD 150193. None of these stars show diffuse nebulosity similar to the envelope surrounding HD 100546, a single star. The disks are not detected by STIS for either HD 104237 or HR 5999, suggesting a small outer radius. The presence of counterjet emission in Lyman α at r$\geq$0.6" in HD 104237 provides further support for interpretation of these disks as being tidally truncated by the 1-2" companions. HD 169142, with 2 M star companions at 8" from the primary, has a remarkably crisp-edged disk, extending only 1.6" from the Herbig Ae star (Raman et al. 2005 [36]), which may make this system another case for tidal truncation of the disk. The situation for HD 150193 is less clear, and may represent a case where the projected primary-secondary distance is not the true distance. The presence of either wide (HR 5999) or close companions (HD 104237, Böhm et al. 2004 [6]) does not appear to affect the frequency of microjets: they are seen equally frequently in the single star systems as in the binary/multiples, at least through 7 Myr.

At this time, there is a sufficiently large sample of coronagraphically imaged Herbig Ae stars that we can begin to say something about how these systems are similar to or differ from star formation in denser aggregates. The available data include 16 fields, with three multiple systems (HD 104237, HD 141569, and HD 169142), two binaries (HD 150193 and HR 5999) and the rest apparently single objects at the resolution of HST. The 31% binary/multiple star frequency in this sample is comparable both to that of that seen in G-K stars in the Solar neighborhood and the Pleiades (Bouvier et al. 1997 [8]), or in dense star forming regions (Padgett et al. 1997 [34], Ratzka et al. (2005 [37]). Additional nearby Herbig Ae stars are known, and some (Fig. 7) are binaries, so the 31% frequency is clearly a lower bound to the true binary fraction, which is likely closer to the Tau-Aur level.

How does the binary/multiple frequency compare with nearby, young stellar associations? Here we can estimate the binary frequency among the A stars using the x-ray detections: the x-ray sources at 8-20 Myr are those with late-type companions, which may be either physical companions or co-moving objects. de la Reza & Pinzón (2004) [12] used the RASS to survey nearby, stellar associations through t=50 Myr. For the youngest associations in the sample, they find an x-ray detection rate for the A star from the RASS of 33% which is very similar to what we observe. The RASS data are incomplete for substellar objects, but *Chandra* with its combination of superior spatial resolution and greater sensitivity can extend such surveys into the sub-stellar regime. When known brown dwarf companions are included (Lowrance et al. 2000 [31]; Tsuboi et al. 2003 [47]) the detection rate increases to 40%, which is comparable to the binary/multiple rate in Tau-Aur (Ghez et al. 1993 [16]; Leinert et al. 1993 [29]; Simon et al. 1995 [40]).

6 Significance of the PMS Multiple Stars:

As noted by Simon et al. (2000 [39]), PMS binary and multiple stars provide the most direct measure of stellar masses, and are crucial in calibrating stellar evolution models, provided the stars are well-resolved. Isolated PMS stars, even those

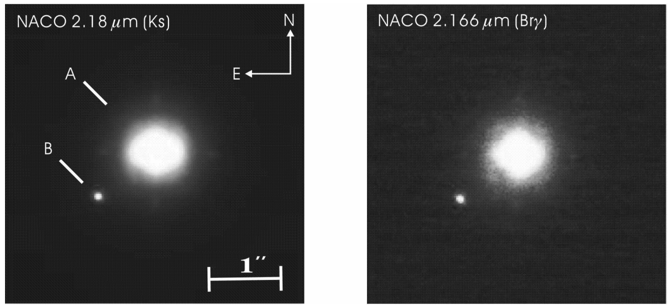

Fig. 7. The newly identified candidate M star companion to HD 100453 (Chen et al. 2005 [10]).

with the best available parallax data are much harder to date and to place into context. These difficulties increase with increasing stellar mass, and luminosity, since the PMS lifetimes shorten. If low-mass physical or co-moving companions can be independently dated using the parallax data for the primary and spectral type and photometry data for the companions, the aggregate can be located in the H-R diagram. The next step is to compare the HR diagram with evolutionary model calculations. This yields a relative dating sequence, if the same model or group of models is used to estimate the ages of several binary/multiple systems, with internal errors as small as 2-3 Myr. This process has been done for the lone A star in the TW Hya association, HR 4796 A/B/C, yielding an age estimate of 8$\pm$2 Myr (Stauffer 1995 [43]), which is consistent with the dating of other confirmed TW Hya association members. In the case of HD 141596 A/B/C, Weinberger et al. (2000) [54] found an age of 5$\pm$3 Myr, in contrast to the estimate of t$\geq$5 Myr based on the A star alone (van den Ancker et al. 1997 [49]). This suggests that the age estimates for other, truly isolated, Herbig Ae stars are uncertain by at least 5 Myr, which is sufficient, in a population with ages which are almost certainly under 10 Myr, to wash out any evolutionary trends.

While different evolutionary models yield slightly different age estimates, the availability of a relative age sequence allows us to make some important inferences about these systems. First, there does not appear to be a simple age-evolution pattern: some systems are largely centrally cleared by 2-5 Myr, while others are still actively accreting at 5 Myr, and producing microjets (Grady et al. 2004 [19]; Swartz et al. 2005 [45]). This is similar age spread in clearing seen in T Tauri stars, and suggests that the evolution of the disk is not strongly coupled to the stellar mass, at least over 0.1-2.5 $M_{\odot}$. If the clearing is associated with planetary mass bodies, rather than brown dwarfs, the available data suggest that giant planets capable of sculpting their host disks can form within a few Myr, a time frame which is intermediate between planet formation-as-mini star models (Boss 2003 [7]) or those which require formation of a 10-15 Earth Mass core and subsequent accretion of a gaseous envelope (Wuchterl et al. 2000 [56]). Rather than representing anomalously gas-rich debris disk systems associated with Main Sequence stars, the disks around HD 141569 A and HD 169142 A appear to have been caught in a potentially short-lived transitional phase, suggesting that the gas lifetime of the disk is shorter than that of the the dust disk.

The nearest PMS multiple systems, particularly those where the companions retain circumstellar material are critical laboratories for probing the chemistry and physics of planetesimal formation. Mid-IR observations of such companions will enable comparative mineralogical studies of the dust, where the only variables are the stellar mass and radiation field. Astrometric studies of the systems with evidence for central clearing will enable the earliest detection of resonances associated with forming giant planets, and may shed light onto planetary migration. High angular resolution imaging, such as will be provided by JWST, and large ground-based telescopes will allow us to probe compositional gradients in protoplanetary and young planetary disks. Finally, with TPF/C it may prove possible to directly image young planets.

Acknowledgements

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