8

Probing the Central Arcsecond: General Astrophysics with TPF

TPF offers a spectacular combination of spatial resolution and sensitivity for general-purpose astrophysical investigations. TPF can be used with baselines as long as 1 km and at wavelengths λ from 2 to 30 μm. The angular resolution at the longest baseline is ~0.25λ milliarcsecond (mas). The sensitivity of TPF will be that of four 3.5 m telescopes, or roughly the same as that of the Next Generation Space Telescope (NGST), yet with 10 to 100 times better spatial resolution. This section highlights some of the astrophysics possible with TPF, ranging from studies of how stars and planets form out of the interstellar medium, how the dust that enriches the interstellar medium with heavy elements forms in supernovae and in the winds from dying stars, and the nature of the engines that power distant starburst and active galaxies.

STAR AND PLANETARY SYSTEM FORMATION AND EVOLUTION WITH TPF

The formation of planets is intimately linked to the birth of stars. From a wide array of space- and ground-based data, we know that protostars surrounded by protoplanetary disks emerge from the gravitational collapse of a rotating molecular cloud core. However, some of the most fundamental questions remain unanswered.

- What determines the mass of a star?
- What generates the ubiquitous collimated jets that are ejected from near-stellar regions in accretion disk systems?
- Do all disks evolve into planetary systems?
- When and how does the planet formation process begin?
- How do dynamical interactions between the disk, star, and evolving planets affect the emergent family of planets?

- What fraction of planetary systems form terrestrial and Jovian planets analogous to those in our own system?

The unprecedented imaging capability of TPF will offer the first direct look at the terrestrial planet formation regime in protoplanetary disks and resolve the region where jets emerge and become collimated. The ability to spatially resolve regions where the key physical processes occur that shape the formation and evolution of stars and planets will provide an extraordinary advancement in our understanding of our origins.

The power that TPF brings to bear on star and planet formation problems resides in its unparalleled angular resolution, its sensitivity, its wavelength coverage, and its spectral capabilities. The 4-element, free-flying configuration for TPF will enable the high angular resolution inherent in the interferometer to be applied in imaging mode, providing pictures of star-forming systems at unprecedented resolution. With 3.5 m apertures TPF will provide superior sensitivity relative to ground-based telescopes at wavelengths longer than 3 µm, even if long baselines become available, because of thermal emission of the atmosphere and telescopes. The wavelength coverage and spectral imaging capability of TPF will probe gas and dust over a considerable range of temperatures and density, ideally matched to those expected in protoplanetary disks, accretion-powered jets, and Jovian and terrestrial planets.

The Nearest Stellar and Planetary Nurseries. The most dramatic gains will be made in imaging forming stars and their protoplanetary disks in the nearest star formation regions. At these distances, with a 1-km baseline, TPF will provide a spatial resolution on the order of 0.1 AU at 3 µm, with a corresponding improvement in resolution at shorter wavelength. Since disk and jet sizes are on the order of 10 to 100 AU, 0.1 AU resolution will yield images of exceptional quality. The scientific return will be very high since these nearest stellar nurseries harbor forming stars and planetary systems in three distinct evolutionary states, spanning an age range from 0.5 to 10 Myr. We discuss each of these in turn.

Embedded Accretion Disks and Core Infall. The youngest stars (0.5 Myr) and their accretion disks are still accumulating mass from remnants of the collapsing core. This natal material rains onto the disk over a range of radii determined by the angular momentum distribution of the core, heating the disk and increasing its mass. During this phase the disks maintain a high accretion rate and can undergo instabilities that radically alter the disk structure and dump large quantities of material onto the star. It is likely that the material infalling from the core is dissipated by the winds generated in the near-stellar region of the disk, terminating the growth of the disk and possibly establishing the mass of the star as well. Observing the distribution of disk material might also help to clarify the nature and origin of companions found in short-period orbits by Doppler studies (Chapter 3), since density waves in the disk have been suggested as one of the processes leading to an inward migration of giant planets. TPF images will clarify the morphology of the infalling material, the jet, and the outflow cavity on 0.1 AU spatial scales (Figure 8.1.). In addition, spectral line images at *R*~100 will provide spatial probes of the accretion shocks above the disk surface and of the interaction between the infalling envelope and the accretion-driven jet.

Revealed Accretion Disks and Planet Formation. After termination of infall of natal material from the core, at least half of the stars maintain active accretion disks for 1 to 10 Myr. These systems have low extinction from obscuring dust, allowing their accretion disks to be directly imaged. We anticipate that they will provide excellent laboratories to study the beginning phases of planet formation, as described below.

Direct Determination Of The Temperature Structure. Determining the temperature structure of a protoplanetary disk is key to understanding its angular momentum transport and ability to form planets. Indirect methods of determining the temperature structure from spectral energy distributions have produced ambiguous results, since they depart significantly from theoretical expectations based on viscous accretion mechanisms. With TPF imaging at 3 to 30 µm, the surface brightness of the inner 10 AU of accretion disks will be mapped, revealing the

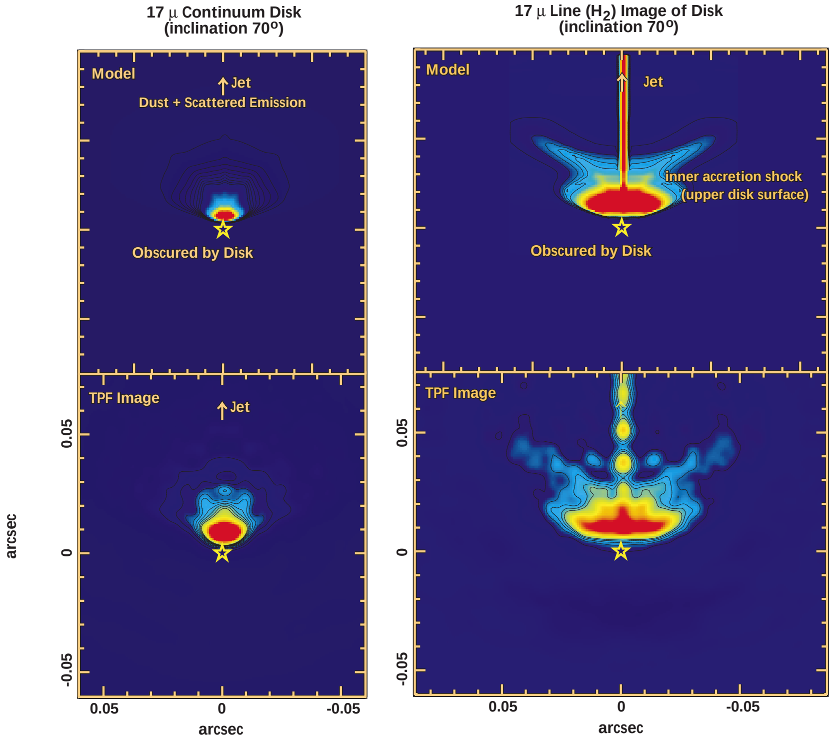

Figure 8.1. Astrophysically important structures would be resolved in the thermal infrared around very young, deeply embedded protostars. The left panels compare the sub-AU structure for a protostar observed nearly edge-on through its disk in the 17 µm dust continuum for a model (upper panel) and as would be seen with TPF. The right panels show a similar comparison in the 17 µm line of H_2, a transition where the jet should radiate strongly. The scale of these images is in arcseconds, so that 0.05 arcsecond tick marks correspond to ~ 7.5 AU at the distance of the Taurus molecular cloud.

location of warm dust ranging in temperature from 1000 K to a few 100 K, providing the first direct determination of the disk thermal profile.

Probes of the Planet Formation Process. The creation of protoplanets in an accretion disk is expected to propagate density waves through the disk and to clear gaps in the disk centered on the protoplanet's orbit. Protoplanetary bodies of Jovian mass can produce disk structure in the form of waves and gaps that can be resolved at the 0.1 AU resolution of TPF, providing extraordinary insight on the growth of planets, the timescale for their formation, and their effect on the evolution of the disk.

Direct Detection of Giant Protoplanets. Young Jovian planets are anticipated to be very hot and luminous in their first 1 Myr. With TPF we will be able to identify the luminosity and temperature of giant protoplanets, providing crucial constraints on the formation of these bodies. TPF will also reveal their distance from the parent star, providing valuable insight on whether giant planets preferentially form at the ice condensation radius and how common orbital migration of planets might be.

Probes of Disk Structure, Chemistry, and Mineralogy. In spectral imaging mode, emission from abundant molecules such as CO, CO_2, H_2O, and solid particles such as silicates and water ice can be used to evaluate compositional gradients and non-equilibrium excitation conditions in protoplanetary disks. For example, trace amounts of material in gaps of dimension 0.1 AU can be illuminated by emission from molecular features such as CO, providing an alternate means of identifying tidally forced gaps. Figure 8.2 shows spectral features of a young stellar object, W33A, which are likely formed in its disk or immediate circumstellar environment. TPF will provide observations of the structure of disks in the lines of minerals, gases, and ices.

Disk Kinematics. An instrument option exists (see Chapter 6) to obtain spectral images at very high spectral resolution (R=100,000). If this option were realized, it would prove to be a powerful probe of the kinematics of disks and accretion shocks, with a velocity resolution of a few km/sec. We could directly test whether inner disks are in Keplerian rotation, and thereby measure the mass distribution in the disk and of the protostar. We could also clarify where emission in spatially unresolved features was arising, by using the velocity profile to infer location in the disk. This would be an excellent means of finding small gaps in a disk where forming terrestrial planets have cleared out a narrow ring.

The Effect of Binaries on Disk Structure. There are many instances of binary stars whose separation is less than typical disk radii. The pair of stars appears to be surrounded by a circumbinary disk with a tidally cleared gap separating the stars from the outer disk. However, both stars can show signatures of outflow and accretion, indicating that

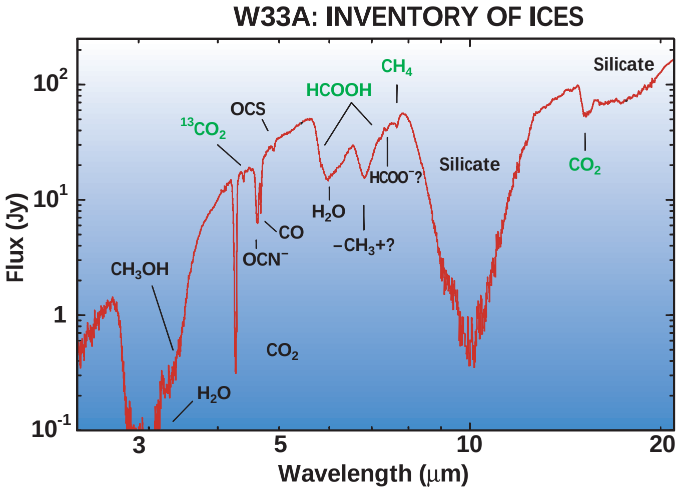

Figure 8.2. This spectrum from the SWS spectrometer on the ISO satellite shows a wealth of information on ices of various species and minerals toward the embedded protostar W33A (Gibb et al. 1998; courtesy of E. van Dishoeck). TPF will study the spatial distribution of such material in the disks of young stars with better than 1 AU spatial resolution.

material traverses the circumbinary gaps and forms accreting circumstellar disks around each star. At 0.1 AU resolution, the tidal effects of companions on protoplanetary disks can be studied directly, providing insight into the survivability of planetary systems around binary stars.

The Origin And Collimation Of Jets. In spectral imaging mode, emission from lines such as H_2 or low excitation forbidden lines will trace the outflowing gas emerging from near-stellar regions on unprecedented spatial scales. Such images should clarify the zone of origin and the means of collimating these extraordinary flows.

Probes Of The Star-Disk Interface. Pushing the spectral imaging capability to shorter wavelengths will provide the ability to study the complex star-disk interface region inside a few tenths of an AU. Imaging at 3 to 5 μm will bring both higher angular resolution and the ability to spatially resolve emission from lines that arise in magnetospheric funnel flows where the star couples to the accretion disk, the innermost regions of the disk, and the base of the wind. These will include features such as the Br series of hydrogen and the CO fundamental.

Post Accretion Disks and Planetary Systems. About half of the low mass stars in the 1-10 Myr age range show no trace of accretion disks or energetic outflows. It is likely that these objects dissipated their disks early on, but whether the disks survived long enough to spawn a planetary system is as yet unknown. An instrument with the sensitivity and angular resolution of TPF is required to determine whether these systems are in an advanced stage of planet formation. Operating in nulling mode, TPF will be able to detect young luminous Jovian planets as close as several tenths of an AU from the parent star, providing additional information on the thermal history and dynamical evolution of giant planets. TPF will also be capable of detecting warm dust in the terrestrial planet forming region to a level of a few times the solar system level of zodiacal emission that might result from heavy bombardment of planetesimals and growing planets. In spectroscopic nulling mode, TPF will determine whether there is sufficient molecular gas to provide a reservoir for the formation of the atmospheres of giant planets, placing firm constraints on the timescale for the formation of Jupiter.

Massive Star Formation. With current observing techniques it has become clear that the formation of massive stars is not merely a scaled up version of low mass star formation. Massive stars are disproportionately more luminous, are produced less often, evolve much faster, and are associated with much more violent events than their less massive counterparts, e.g. powerful bipolar jets and outflows, high velocity stellar winds, high velocity masers, and, last but not least, supernova explosions. High mass stars supply the galaxy in which they form with the ingredients for interstellar dust and molecules and due to their energetic outflows and death throes as supernovae, they are largely responsible for the interstellar turbulence which ultimately leads to the production of magnetic fields via a galactic dynamo and thus to the acceleration of cosmic rays, which in turn are important to the thermal balance in the interstellar medium. In this manner, massive stars control the global star formation rate and possibly the initial mass function in a galaxy and thus play a key role in determining its overall evolution.

Understanding the principles of high-mass star formation on a “local” level will thus provide important constraints for understanding the evolution of galaxies and luminous matter on a cosmological scale. Previous attempts to “bridge the gap” between what we know about star formation locally and what we need to know about it on a global scale have been hampered by lack of both sensitivity and angular resolution. Because of a combination of the rapid fall off of the efficiency of producing high-mass stars and their extremely short evolutionary time scales, only a few local sources are available for study with current means or with instruments available in the near future, say at distances of the Orion Trapezium cluster. Even at these distances, the picture is further complicated by confusion due to multiple sources and the complex, manifold interactions of their local circumstellar material and outflows.

Thus, it will be of extreme interest to use the angular resolution in conjunction with the sensitivity of TPF to study a few of the brightest objects in Galactic star formation regions in which both low-mass and high-mass star formation are currently taking place, as for example in Orion (1500 light years ~ 0.5 AU resolution) and in NGC 3603 (20,000 light years ~ 7 AU resolution). TPF will still provide many orders of magnitude improvement in angular resolution over any other telescope in imaging disks and jets around high-mass stars; it will allow us to compare jets in high- and low-mass stars and to differentially assess the effects of a strong radiation field; it will yield insight on protoplanetary disks around low mass stars being photoevaporated by nearby high mass stars and allow crowded clusters to be resolved into individual stars. Turning to the closest extragalactic star forming regions such as 30 Doradus in the Large Magellanic Cloud (165, 000 light years ~ 50 AU resolution) will allow us to differentially assess the role of a lower abundance of carbon, nitrogen, oxygen, etc. on both low-mass and high-mass star formation, effectively “turning back the clock” to earlier epochs of our own Galaxy, during which these element abundances were also lower.

Evolution of Planetary Systems. With TPF, we will be able to observe planetary systems in a wide range of evolutionary states, advancing planetary science from case studies of individual objects in a few systems, into a systematic understanding of the frequency and diversity of planetary families that inhabit the Galaxy. Moreover, the evolution of planetary systems, including the thermal history of giant planets, the atmospheric evolution of terrestrial planets, and the dynamical evolution of all orbiting bodies, will be amenable to direct observation.

There are many components of planetary systems that can be observed with TPF that are anticipated to evolve substantially with time. Giant planets will be formed with high initial temperatures, but will slowly cool off. Terrestrial planets will undergo atmospheric evolution resulting from internal processes, from bombardment by comets, and from changes in heating resulting from the evolution of their parent stars. Orbits of large comets will reflect their origin, and their chemical abundances will reflect both their origin and history. The magnitude and spatial distribution of Kuiper belt dust, already observed around some nearby stars, can provide indirect probes of the dynamical evolution of outer planets. The magnitude and spatial distribution of asteroidal dust, not yet detected in any system other than our own, can provide indirect probes of the dynamical evolution of terrestrial planets and asteroids. Tidal encounters with neighboring bodies or disk material can cause significant dynamical evolution of planetary orbits, possibly creating planetary systems that look significantly different from our own.

Chronological studies of planetary system evolution will be enabled by the presence of nearby star clusters spanning ages from 10 to 100 Myr and solar neighborhood stars with ages up to 10 Gyr. One of the youngest nearby clusters is the Pleiades, at an age only 1/100 that of our own solar system. Although it is 130 pc away, Jovian planets in this cluster are predicted to sustain Earth-like temperatures, making their detection comparable to that of an Earth-like planet at a distance of 12 pc. At this relatively young age, there may also be considerable asteroidal or Kuiper belt dust that might be detectable with sensitive nulling observations. The Hyades cluster at a distance of only 40 pc is about 1/10 the age of our solar system. Its nearer distance, translating into a tenfold increase in threshold detection levels compared to the

Pleiades, more than compensates for the anticipated cooling of giant planets at this age. Planetary systems comparable to, or older than our own solar system, will be available for study in the immediate solar neighborhood, further extending chronological studies with TPF.

The above predictions reflect our current concepts of planetary evolution. However, the cooling of white dwarf stars proved to be far more complex than anticipated because of effects due to crystallization. We fully anticipate that our predictions for the cooling of giant planets are similarly naïve and that TPF observations will offer surprises and new physical insights. We also expect a rich diversity in the atmospheres of terrestrial planets. Mars was once warm enough to have liquid water on its surface. Venus is believed to have once had abundant atmospheric water, which it subsequently ejected in large quantities. We can expect that evolutionary effects similar to these will be observable in extrasolar planetary systems, giving us further insight into the origin and evolution of our own life-giving atmosphere.

Targets and Integration Times. Nearest stellar/planetary nurseries: At 10 µm, the accretion disks in the nearest star formation regions, such as Taurus and Ophiucus, are bright enough to be readily detected as unresolved objects with 3 m ground-based telescopes. However, imaging these disks at 10 µm will require the full sensitivity of a spaceborne interferometer due to the reduction in flux per pixel when the disk is spatially resolved. For example, if the 10 µm emission comes from a circular area of radius 10 AU that is uniformly bright, it will be spread out over $100 \times 100 = 10^4$ pixels, with a corresponding reduction in flux per pixel of a factor of 10^4 ($\Delta m = 10$ mag). Typical accretion disk systems have integrated magnitudes at 10 µm of ~6 mag, resulting in a surface brightness of ~16 mag/pix when observed with TPF at milli-arcsecond resolution. Sensitivity models of the telescope performance indicate that six hours of integration time on such an object will yield an *SNR* of 10 per pixel at a spectral resolution of ~20. With the overhead associated with maneuvering the spacecraft to achieve good *uv*-plane coverage for high dynamic range imaging, mapping a single accretion disk at a distance of 140 pc will take approximately 1 day. Spectral line imaging of a disk/jet system at $R \sim 100$ will take a few days per object, depending on the complexity of the source. The spectral energy distribution of a simple model for a disk is shown in Figure 6.11 to illustrate TPF's sensitivity after 1 day of observation for spectral line ($R\sim100$) imaging.

UNDERSTANDING THE FORMATION OF INTERSTELLAR DUST, THE BUILDING BLOCKS OF PLANETS

Origin of Dust in the Interstellar Medium. The terrestrial planets were formed by the agglomeration of smaller objects—planetesimals—which themselves were built up of tiny grains of dust, some from the original interstellar matter out of which the star formed, and

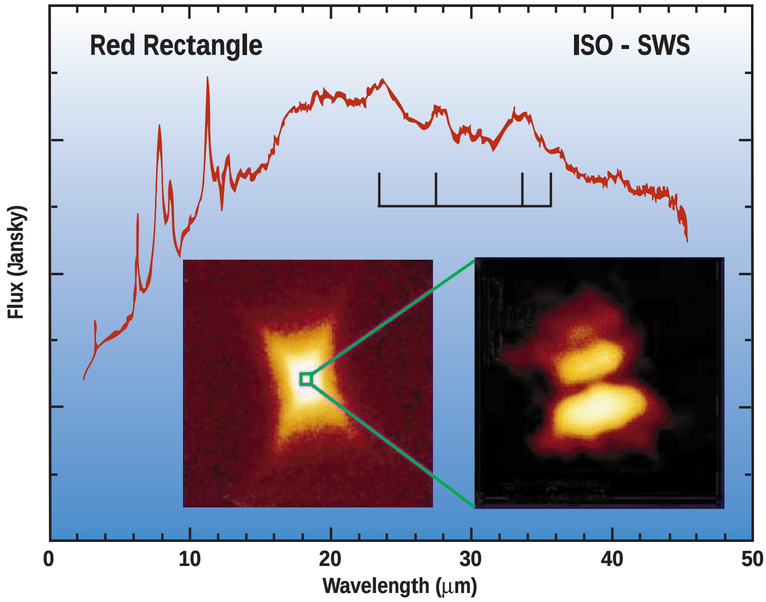

Figure 8.3.
A spectrum from ISO shows emission features of the oxygen-rich mineral olivine (marked with vertical lines) as well as many other minerals in the dust surrounding a pair of dying stars called "The Red Rectangle." Also shown are ground-based near-infrared images that reveal a dust disk surrounding the binary system that may be a region of delayed planet formation. TPF will probe the detailed structure of this region with 100 times better spatial resolution than the best ground-based images. (spectrum courtesy of ESA, left image: H. van Winckel, right image: G. Weigelt and R. Osterbart)

some freshly condensed from the iron, silicon, aluminum, and oxygen in the cooling hot gas of the protostellar accretion disk. Meteorite samples incorporate silicon carbide (SiC) and aluminum oxide dust grains from old, cool, mass-losing Asymptotic Giant Branch (AGB) stars, as well as TiC grains formed in the explosions of massive stars, type II supernovae. Ultimately, the heavy elements that condensed into these dust grains were formed deep in the cores of an earlier generations of stars and ejected into interstellar space for recycling by either winds from dying stars or in giant supernovae explosions. TPF will be able to probe AGB stars, supernovae, novae, and planetary nebulae at the spatial scales, with the sensitivities, and the wavelengths critical to exposing the physical processes that lead to the nucleation and formation of grains:

- Understanding how grains nucleate and grow in outflows of stellar winds, novae, and supernovae will help us to understand how grains nucleate and agglomerate in the early solar nebula.
- Characterizing interstellar grains will reveal the complex organic gas-grain chemistry that creates prebiotic materials such as amino acids materials, which are later delivered to protoplanets, possibly as the building blocks of life.
- Linking the evolution of dust chemistry to the evolution of accretion disks and agglomeration of protoplanets may give spectroscopic probes for the evolutionary status of remote planet forming systems.

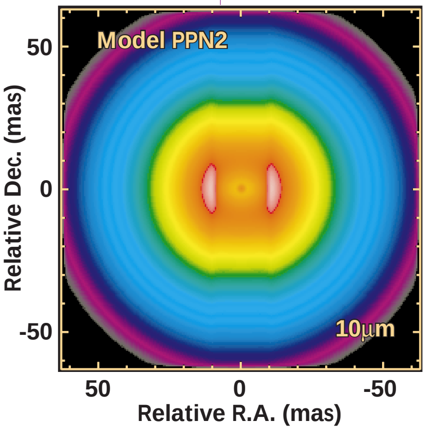

Figure 8.4. A simulated TPF image of milli-arcsec structure of the wind emanating from an AGB star in the post-planetary nebular stage. TPF will have the angular resolution to investigate the process of dust formation in stellar winds. (Courtesy of A. Dayal)

Dust formation in AGB Stars. Dust condensation in AGB stars occurs at about 10 stellar radii from the low gravity stellar surface, at the same radii that the stellar wind appears to be accelerated by radiation pressure on the grains. However, according to grain nucleation theories and laboratory experiments, the growth process must start ("nucleation") with small seeds that form at higher gas densities at only a couple of stellar radii. It is suggested that tiny iron-poor highly refractory grains such as sapphire (Al_2O_3) nucleate at two stellar radii, drift slowly to the outer radii zone where the temperature decreases to the point where iron-containing silicates condense on these nucleation seeds. Then rapid grain growth occurs, and due to the iron content, these growing grains absorb photons efficiently, accelerating, colliding with the gas, and driving the stellar wind. Alternatively, clumping in the outflow raises the effective density locally, allowing grains to nucleate and condense at tens of stellar radii. TPF will make infrared images with < 10 mas resolution in the continuum and in the features of species such as the Si-O (8.0 – 12.5 μm) and Al_2O_3 (13.4 μm) to probe the dust nucleation zones in AGB stars, exposing the physical processes that lead to interstellar grains and to solar nebula condensates.

Dust from Supernovae. While about half of the dust grains in the interstellar medium come from AGB stars, half are thought to form in type II supernovae. The only direct observations we have of dust condensation in supernovae is from our study of the brightest supernova in 400 years, supernova SN1987A (Figure 8.5) in the Large Magellanic Cloud. About 600 days after SN1987A exploded, dust condensed, and, within a couple of months, blocked out 95% of the light of the object, converting it from an optically bright nebula into an infrared "dusty rusty" object, rich in iron grains (Wooden *et al.* 1993). TPF would have been able to observe the dust condensation process directly, finding clumping in the ejecta, following the formation of molecules, and monitoring the dramatic transition into an infrared object. While another such nearby bright supernova may not occur within this century, imaging of very young supernovae is possible in more distant galaxies.

STARBURST GALAXIES AND BURIED AGN AT THE EPOCH OF PEAK STAR FORMATION

Starburst Galaxies. The recent detections of far-infrared sources using the ISO satellite (Clements *et al.* 1997) and of powerful sub-mm sources (Smail *et al.* 1998; Barger *et al.* 1998) using the Submillimetre Common-User Bolometer Array (SCUBA) (Holland *et al.* 1997) raises the interesting possibility that these bright sources correspond to the building of the cores of galaxies near the epoch of peak star formation (z~1-4). It is important to emphasize that the optical identifications of these sources, and hence their redshifts and luminosities, are not secure. Nevertheless, several studies find that the integrated luminosity from these sources would, with modest extrapolations to slightly fainter flux levels and shorter wavelengths, represent the majority of extragalactic background light at far-infrared and sub-mm wavelengths (Clements *et al.* 1997; Hauser *et al.* 1998; Fixsen *et al.* 1998). This background is almost certainly due to the reprocessing of ultraviolet flux into mid-IR, far-IR, and sub-mm radiation. Hot, young stars are the most likely source of the ultraviolet radiation, with AGN a close second. That SCUBA finds relatively few sources responsible for much of the background points to extraordinarily high star-formation rates, hundreds of solar masses converted to stars per year (brighter than Arp 220) or bright AGN ($> 10^{46}$ erg/s). In either case, ISO and SCUBA are detecting a major epoch of formation: bulge formation in early galaxies or the growing of massive black holes (Richstone *et al.* 1998.) Distinguishing between these scenarios will be a task for future observatories: NGST (the most sensitive with sub-arcsecond resolution), Space Infrared Telescope Facility (SIRTF) and the Far Infrared and Submillimeter Space Telescope (FIRST) (arcminute resolution but best sensitivity at the peak of the spectral energy distribution or SED), and the Millimeter Array (MMA).

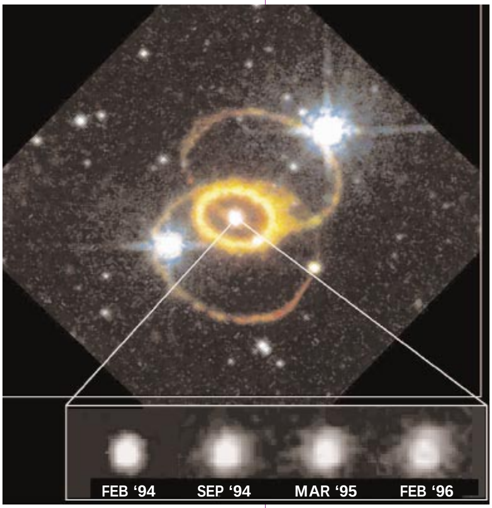

Figure 8.5. An HST image of SN1987A reveals blobs of ejecta (lower panel) moving away from the site of the exploding parent star. TPF will image these blobs with 10-100 times better spatial resolution in and out of various spectral lines of solid state and gaseous species.

TPF will play an important role in resolving the mid-infrared radiation in these SCUBA sources. From 3-30 µm TPF will be observing the radiation from warm dust (Polycyclic Aromatic Hydrocarbon (PAH) emission in the photo-dissociation regions surrounding the compact sites of star formation or heavily obscured active nuclei at redshifts z~1-2. TPF resolution with a 200 m baseline will be ~20 mas, with <0.1 µJy sensitivity for a 1 day observation in a broad spectral band (R~5). This sensitivity is more than sufficient to detect and image an Arp 220-like source at a redshift of z ~ 1, (F_ν(15 µm) ~ 0.2 µJy). The angular resolution corresponds to a physical scale of 170 parsec, comparable to the 364 pc separation of the two nuclei/regions in Arp 220 (Scoville *et al.* 1998). Thus, TPF will be capable of either resolving the star-forming region or discovering the point-like source, << 100 pc, expected in a buried AGN. It is important to note that some of the tentative identifications of SCUBA sources suggest luminosities 3-5 times greater than Arp 220. Such sources will be observed and imaged with TPF to higher redshifts and at longer wavelengths. TPF will provide a unique combination of resolution and sensitivity, unmatched by NGST (~8 m baseline) or the Very Large Telescope (VLT) (10^6 more background). Thus, it will uniquely be capable of imaging the luminous nuclei and structures in these bright

SCUBA sources, close to the peak wavelength of their SED.

IR Interferometry of AGNs. Research on active galactic nuclei (AGNs) and the host galaxies surrounding them has reached an exciting threshold. As evidence for supermassive black holes at the centers of galaxies continues to roll in (e.g. Richstone *et al.* 1998), demonstrating that these objects are the norm for galaxies, rather than the exception, studies of quasars and other AGNs are beginning to mesh with studies of galaxy evolution in general. Questions about how giant black holes form and grow now appear intimately related to questions about how galaxies themselves form. Yet, we remain largely ignorant about how quasars and other AGNs interact with their hosts. Infrared interferometers operating at 2 to 20 µm over >100 m baselines will be very useful for clarifying these issues because they will be ideal for probing the interfaces between active galactic nuclei and their hosts.

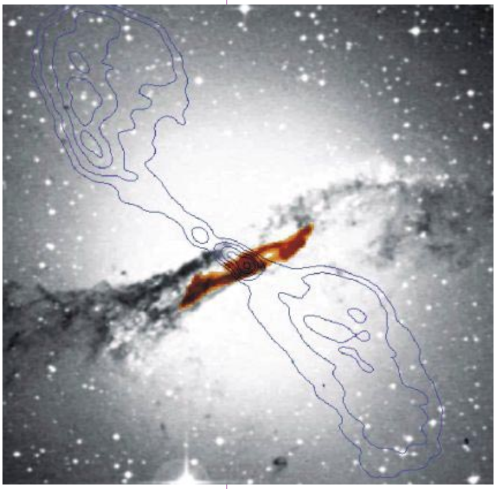

Figure 8.6. A flat, disk-shaped galaxy, seen almost edge-on (infrared image in red), has collided with a large, round, elliptical galaxy (visible light in black and white) to make the peculiar object known as Centaurus A. The infrared image from ISO (Mirabel et al., in preparation) reveals the spiral galaxy for the first time. A black hole, fueled and possibly even formed by the disruption of stars and gas in the violent collision, is at the center of the spiral galaxy. Emission of material ejected from the black hole is responsible for the jets of radio emission shown as blue contours. TPF will probe the structure and physical conditions in accretion disk surrounding the black hole.

Nuclear activity in galaxies occurs when a supermassive black hole is actively accreting interstellar gas. Exactly how galaxies manage to channel enough gas into such a small volume remains unclear; however, it seems unlikely that a galaxy could accumulate enough dense gaseous fuel at its center without igniting a burst of star formation as well. Disentangling the phenomena associated with a starburst from those associated with an AGN is tricky because the interface zone between an AGN and its host is only tens of parsecs in size, subtending an angle of less than 100 milli-arcseconds (mas). But if we are to determine how AGNs are fuelled or to learn whether an AGN predates a central starburst or vice versa, this is the crucial region to study.

The 1 mas beam size of a ~1,000 m mid-IR interferometer is well suited for studying the ~100 mas interface regions of the brightest AGNs (e.g. Voit 1997a), and a larger interferometer could perform similar studies of distant quasars. Thermal emission from AGN-heated dust in the interface region peaks in the mid-IR, and numerous emission features from fine-structure emission lines (e.g. [Ne II] 12.8 µm, [Ne III] 15.6 µm, [Ne V] 14.2 µm) and small carbonaceous particles (e.g. 3.3 µm , 11.3 µm) are also present. Mapping the thermal emission will reveal the spatial distribution of the fueling gas clouds on the crucial scale between Hubble Space Telescope (HST) (100 mas) and Very Long Baseline Array (VLBA) (1 mas) and will establish the relative contributions of the starburst and the accretion engine to the nuclear activity. Imaging the mid-IR emission features will provide information on the density, velocity, and obscuration structure of the interface gas and will also reflect the anisotropy of the AGN emission. Finally, nulling interferometry of the broad line emission from the nucleus could help to establish the mass of the central black hole (Voit 1997b).

COSMOLOGICAL DEEP SURVEYS AND CONFUSION NOISE

As is often the case in astronomy, one person's noise is another person's signal. While deep galaxy counts are of primary interest to cosmologists, the unevenness in the background caused by the distribution of faint galaxies could produce confusion noise for TPF's search for planets. NGST will eventually make deep infrared images with 0.1″ resolution, enough to resolve almost all galaxies. However, TPF's angular resolution on modest baselines (~100 m for resolution of a few tens of milli-arcsecond at 10 µm) will be invaluable for determining the internal structure—spiral arms, star forming clusters, etc.—of the most distant galaxies detected by NGST.

The major contributors to the confusion noise are galaxies, stars and cirrus. Order of magnitude calculations indicate that none of these sources is likely to be a serious problem for TPF's search for planets, although perhaps of interest to cosmological researchers. If galaxies were simple point sources, then galaxy evolution models constrained by IRAS and ISO data predict 12 µm confusion noise levels far below 0.1 µJy for a 0.1″ beam. However, even if galaxies are treated as extended sources, it is possible to show that they will not be a problem for TPF. While it is not known how the mid-infrared emission is distributed in these faint, far-away galaxies, suppose that (1) most of the sources contributing to the background are at redshifts z~1; (2) the mid-infrared emission disk of these galaxies can be approximated by a Gaussian with a Full-Width Half-Maximum (FWHM) of 10 kpc. Then in the 12 µm rest-frame these galaxies will appear as a Gaussian with

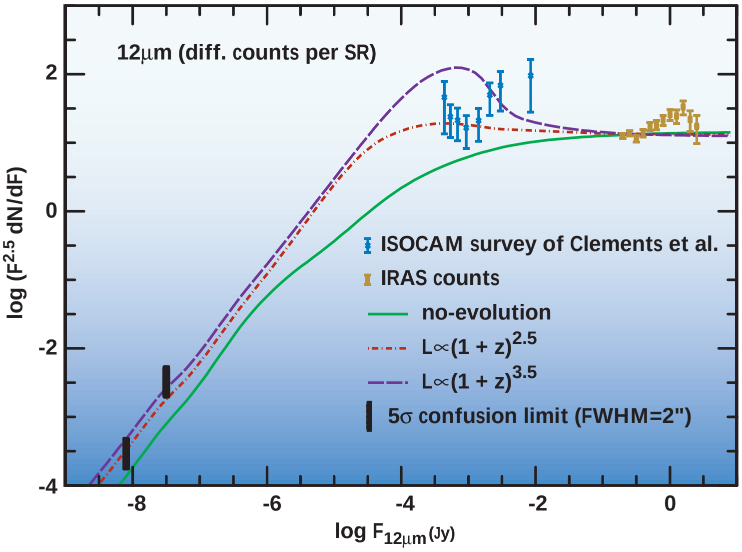

Figure 8.7. Calculations of the integral source counts for galaxies seen at 12 µm, under various assumptions about the degree of evolution, indicate that confusion from galaxies should not be a problem for TPF.

a FWHM of ~2″ (for a q_0=0.5 and H_0=75 cosmology, a 10 kpc source at z=1 has an angular size of 1.7″). The confusion noise due to these galaxies in a 0.1″ beam is very much the same as the confusion noise due to point-like galaxies to a 2″ beam. The confusion noise (1σ) due to such extended galaxies is in the range of 0.001-0.007 µJy, far below the brightness of an earth. (Figure 8.7). Unless there is a new population of starburst galaxies beyond z~1 (the limit of ISO observations), confusion noise should be negligible for TPF's search for planets. However, any particular target star may have confusing background stars or galaxies whose effects may be mitigated by observing at multiple epochs; the nearby target star and any associated planets will appear to move while distant background objects will not.

Thus, while distant galaxies will not be a problem for TPF's primary goal of planet detection, TPF will be able to bring its spatial resolution and NGST-like sensitivity to bear on important problems in galaxies at cosmological distances.

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