Planetary Systems and Star Formation with JWST

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The birth of stars and protoplanetary systems is one of the four defining science programs for the James Webb Space Telescope (JWST). This telescope will also have unique capabilities to probe the overall evolution of exo-planetary systems. Studies with JWST of planets themselves both within and outside of our own system are discussed in white papers by Sonneborn et al. and Clampin et al. Here, we describe the JWST ability to:

- **Trace the path from interstellar clouds of gas and dust to stars**
- **Understand the process of stellar formation itself**
- **Determine how planets form in dense disks of gas and dust around young stars**
- **Probe the subsequent evolution of planetary systems**

1. Trace the path from interstellar clouds to stars

Star formation starts in molecular clouds. Turbulence and magnetic fields control the configuration of these clouds, twisting and shredding them into sheets and filaments. These structures sometimes collapse, forming cold dense cores shielded by dust from damaging ultraviolet photons.

We detect this dense gas and dust throughout the observable Universe, comparing it with tracers of newly formed stars. We are puzzled. *Why does the efficiency of star formation vary by huge amounts?* For example, in our neighborhood stars are born at a low rate, but there is runaway star formation in the centers of some galaxies that is consuming the molecular gas virtually instantaneously. The answer must lie in the means by which magnetic fields and turbulence support clouds against compression, support that must be overcome for them to collapse and stars to be born. The first steps toward life may also

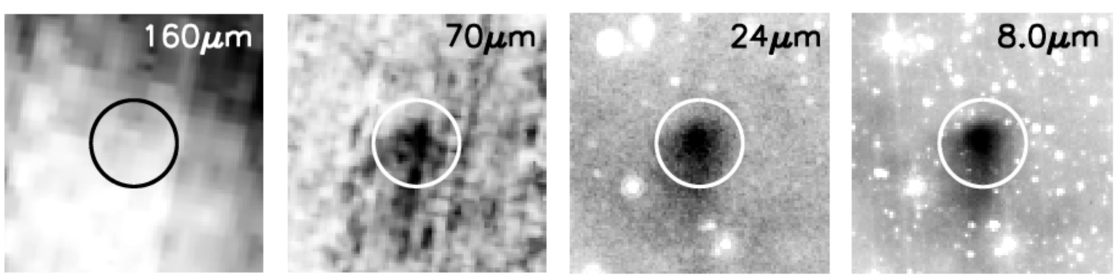

Figure 1 from A. Stutz (private communication and Stutz et al. 2009), a collapsing core shadow at 24 μm (MIPS and IRAC 4' × 4' images of L429). The circle (radius = 40") indicates the location of the shadow produced by the dense core material. The images are displayed on a log scale; north is up and east is to the left. This core appears to be optically thick at 24 μm over a region 10 – 15 arcsec in radius. The compact size and high density indicate that this core is either starting its collapse or very near to starting it.

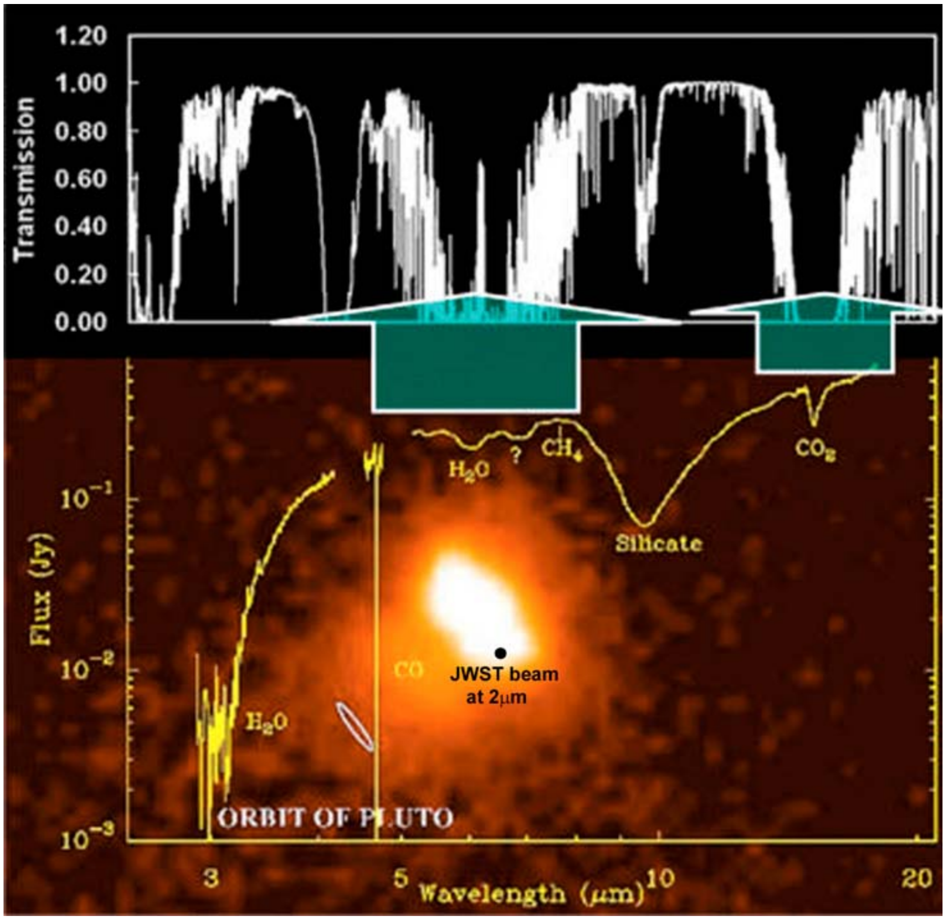

Figure 2. Spectrum and image of the protoplanetary disk around CRBR 2422.8-3422 (lower panel, Pontoppidan et al. 2005, ssc2004-20 press release). The shape of the feature marked with ? indicates that it arises in the nearly edge-on protoplanetary disk. The upper panel shows the atmospheric transmission from a dry site. The shaded arrows show the relatively transparent regions in the interstellar medium (delineated by strong extinction up to 5 μm and the silicate absorption between 8 and 12 μm). There is a rough anti-coincidence between atmospheric and interstellar windows, emphasizing the importance of space data to probe important prebiotic organic materials and water.

take place in the dense molecular cores, where chemical processes drive the synthesis of complex molecules, solids, and ices. *How does the flow of the elements shape the molecular clouds, the formation of stars, and the nature of their attendant planetary systems? What drives prebiotic chemistry in these environments?*

To understand the processes controlling the fragmentation of molecular clouds, we need to understand the structures of pre-collapse and collapsing interstellar globules. This information can be provided by studies of background stars shining through them and even by detecting shadows against the diffuse background emission (Alves et al. 2001, Stutz et al. 2009). **For example, at a distance of 200pc, JWST will be able to probe cloud core structure with NIRCam and MIRI on a scale of 100 AU or smaller.** Once it starts to form a star, the cold core of a collapsing globule is frustratingly difficult to penetrate to see what is happening. However, there are interstellar absorption “windows” near 6 and 15 μm (see Figure 2) that can be used to probe the core and particularly the region where the protostar is forming. **The NIRSpec and MIRI spectrometers will be sensitive to cool molecular hydrogen and can probe the chemistry occuring in the cloud as its gas is warmed by the process of star formation.**

2. Understand the first stages of collapse into stars

After a dramatic initial collapse, a protostar grows for about a hundred thousand years as gas and dust flow onto it from the surrounding cloud. Eventually the new star stabilizes, heated by the energy released as gravity continues to compress it. These processes are only vaguely understood. *What sets the mass of the final star? Why do stars have a specific distribution of masses strongly favoring low mass stars over high mass ones, nearly everywhere both within and beyond our galaxy?* The similar distribution of stellar masses persists over a wide range of conditions for star formation and despite the variety in star forming efficiency. It defies the theoretical prediction that the amount of mass that can collapse gravitationally into a star depends on the temperature and density of the ambient gas. We need to study star formation over a wider range of elemental abundances, gas pressures, and magnetic field strengths to seek how the starting conditions influence the resultant mass distribution. We must search for low-mass brown dwarfs down to the mass of Jupiter to detect clearly the minimum mass formed in the fragmentation process, predicted to be a few times larger than that of Jupiter. A related issue is how conditions are established that allow formation of binary stars and planets. Millimeter wavelength observations reveal that significant amounts of gas and dust, often more than enough to form a planetary system, are left in disks around new stars. *How is the star built up while leaving the surrounding pre-planetary material? What determines if the surrounding material forms a planetary system, a second star, or merely escapes back into empty space?*

Several specific observations are needed to probe these questions. First, we need to compare the mass distribution of pre-stellar cold cloud cores to the mass distribution of newly formed stars to see how a cloud fragments. Second, we need to understand how pre-stellar and star-forming cores lose rotational energy to avoid spinning apart as they collapse into the youngest stars. Third, we need to understand the powerful jets and winds associated with young stars, including the mechanical energy they transfer into the surrounding material. It is possible that these flows eventually overpower the gravitational attraction of the remnant matter, terminating the growth of the star. Fourth, we need to probe the material around forming stars to understand what controls its fate. Finally, we need to identify the products of individual star-forming clouds, over a wide range of age and mass, down to the mass of Jupiter.

JWST shadow maps of cloud cores, combined with submm- and mm-wave spectra, will measure the dynamics and morphologies of collapsing clouds with sufficient detail for comparison with hydrodynamic simulations. **For example, The JWST beam diameter of a few tens of AU** (for the nearest star forming regions) **is well suited to probing the**

process of star and planet formation at critical scales. It will enable spectroscopic mapping of shock fronts in lines such as molecular hydrogen, with a wealth of lines from the near infrared to 28 μm. The spectrometers on JWST will search for prebiotic molecules, such as water and simple hydrocarbons, which have very strong transitions in the JWST spectral range. Many of these species can be studied effectively in the interstellar windows. JWST spectra will also probe other aspects of the chemistry occurring in the central regions of the youngest protostars.

Once star formation is under way, radiative transfer models (e.g., Boss & Yorke 1995) predict that there should be enhanced emission in the mid-infrared, up to three orders of magnitude above the characteristic (20K) blackbody output of the core at some wavelengths. This emission arises from scattering by dust of the emission of the warm central source; the degree of scattering is a strong function of the density distribution in the envelope of the young protostar.

JWST can measure the spectral energy distribution of this output through the interstellar windows to provide diagnostics of the envelope structure. JWST imaging will also be able to probe whether the core is forming a single star or a binary. Combined with measurements of the density structure of the cloud (e.g., Section 1) and the dynamics, using submm- and mm-wave spectroscopy, we may be able to distinguish the conditions that lead to binary formation.

When the new stars emerge from their cold cocoons, JWST will have adequate sensitivity to identify young objects down to the mass of Jupiter in the nearest star forming regions. A combination of multi-band imaging and spectroscopy will penetrate the extinction in the near infrared and allow unambiguous identification of young low-mass stars and brown dwarfs. The small JWST beam and high sensitivity will also let us identify minimum-stellar-mass objects in young clusters at kpc distances. For example, **even at 25μm JWST can detect 0.1 solar mass objects at 1 kpc** in integrations of about an hour; the beam diameter of 0.005pc will avoid confusion with signals from other brighter objects in a cluster. These investigations will provide a definitive look at the mass spectrum of recently formed stars and brown dwarfs.

3. Determine how planets form in dense disks of gas and dust around young stars

Snapshots of the evolution of young disks are provided by images in scattered light, both with HST and from the ground. Because such observations are limited in surface brightness sensitivity, they have been successful primarily on the relatively dense disks that are emerging from the protoplanetary stage. It is often found that these disks have marked asymmetries and complex structures possibly associated with gravitational instabilities, either within the disk or due to perturbations by passing stars. *What processes shape these young disks, and how do they lead to the formation of gas giant planets? Or do these planets form in an entirely different way by accretion onto cores of heavy elements?*

JWST will image young disks in individual molecular lines in the near and mid-infrared, such as shock excited molecular hydrogen, and in fine structure lines such as [NeII] and [ArII]. The beam sizes will range from that of Figure 2 (at the hydrogen recombination and molecular hydrogen lines near 2 μm) to about five times larger (at [NeII] at 12.8 μm), allowing the systems to be resolved and the range of excitation and shock conditions to be mapped over the systems.

Another probe for the formation of gas giant planets is provided by transit measurements, which can test for the existence and size of cores of heavy elements. The possible correlation of the radii of hot Jupiters with the metallicity of the star suggests that core accretion may be the dominant formation mode, a suggestion that will be tested definitively with JWST. Further details are provided in the white paper on transit observations by Mark Clampin et al.

Although gas giants must form very quickly, it is believed that terrestrial planets have a much longer incubation period (e.g., Kenyon and Bromley 2004). However, there are not nearly enough *nearby* young disks to probe the predicted overall time dependence of this critical phase in planet evolution. There are indications of the expected behavior only for more massive stars, based on observations of relatively distant clusters to both constrain the stellar age and to obtain adequate statistics (Currie et al. 2008). **The resolution and sensitivity of JWST will allow us to characterize circumstellar disk evolution during the critical 5 – 30Myr period** in dense clusters out to 2kpc and down to well below solar mass stars.

4. Planetary System Evolution

Even after the protoplanetary disk has faded away, terrestrial planet formation continues to be marked by collisions. *How fast do these systems settle down? What is the incidence of catastrophic collisions, such as the one that led to the formation of our Moon? Are the steps deduced for the formation and evolution of planets in the Solar System typical or exceptional in other systems?* Although the earth-sized planets in young systems are beyond the reach of our current telescopes, when they and smaller bodies collide, they produce debris particles. These particles are heated by the star and can be detected as an excess of infrared output above the level of the stellar photosphere. The particles are lost quickly due to non-gravitational forces, resulting either in their being ejected from the system or spiraling into the star. As a result, maintaining debris disks requires that there be continuing collisions among larger bodies to replenish the particles. Such collisions continue for a long time after a planetary system has formed and stabilized. For example, within the solar system, collisional debris continues to be produced in the asteroid and the Kuiper belts. The characteristics of the resulting debris systems provide a measure of the evolution of planetary systems into the Gyr age range. In fact, debris disks are at present virtually the only way to probe events in large numbers of planetary systems outside the zones that we can study through Doppler recoil and planetary transit measurements.

Spitzer, Herschel, and WISE will complete our census of debris disks, initiated with their discovery by IRAS. We already know of hundreds of them, but except for a few nearby examples, we have little understanding of their structures beyond a modest distribution of points on a spectral energy distribution. From the well-studied examples, we understand that the structures are likely to be better-described as debris rings rather than disks, and that the rings may be shepherded by planets. Fomalhaut is a dramatic example, with a Jupiter-mass planet circulating at the inner edge of its debris ring (Kalas et al. 2008). The system of massive planets recently discovered around HR 8799 (Marois et al. 2008) is accompanied by an anomalously cold debris system, again suggesting a ring shepherded by the planets.

However, photometric SEDs, even with well-sampled spectra, are degenerate between structure and the optical properties of the debris particles. To understand debris disks and rings requires well-resolved imaging. Spectroscopy can also reveal aspects of disk structure not accessible to imaging. For example, the presence of mineralogical features typically indicates the presence of small grains with short lifetimes against loss (e.g., Beichman et al. 2005; Lisse et al. 2007). The exceptionally bright and well-resolved system around beta Pic shows changes in the grain properties with increasing distance from the star (e.g., Weinberger et al. 2003, Okamoto et al. 2004), a key ingredient to understanding the composition and evolution of the debris and its parent bodies. A few debris systems are dominated by photon-pressure-sustained winds of small particles (Krivov et al. (2000) for beta Pic, Su et al. (2005) for Vega). This behavior probably results from significant stirring of asteroid systems or major individual collisions that lead to a dramatic series of collisional avalanches. Imaging these systems well enough to resolve the debris rings separately from the winds can allow us to understand violent phases of planetary system evolution.

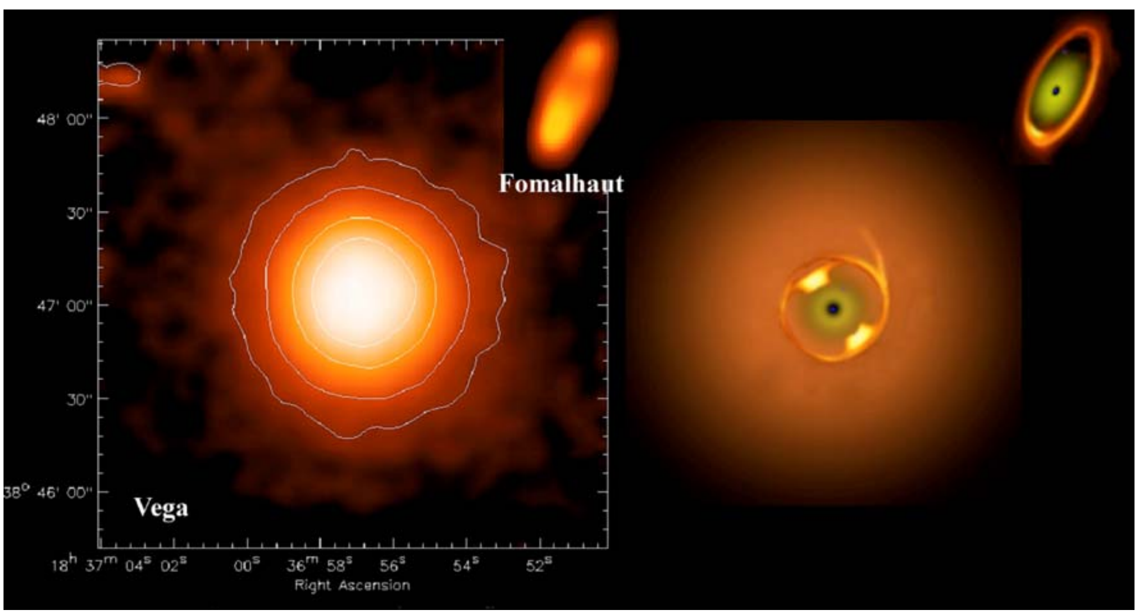

Figure 3. Vega and Fomalhaut. The images to the left are from Su et al. (2005) and Staplefeldt et al. (2004), both released by the Spitzer Science Center. Those to the right are concepts of what the systems might look like as observed with JWST at 24 μm.

The long wavelength bands of JWST will greatly advance our imaging capability for debris disks. The 15.5 and 23 μm coronagraphs will suppress the star and search for faint features close to it that would otherwise be lost in the wings of the PSF. The larger scales can be probed by conventional psf-subtraction. The MIRI IFU will support resolved spectroscopy across a wealth of debris disk amorphous and crystalline silicate spectral features documented in ISO and Spitzer spectroscopy. In cases with relatively high optical depth, the NIRCam and TFI coronagraphs will obtain images in scattered light, similar to those now observed with NICMOS but with a significant gain in sensitivity and, as desired, spectral resolution. The full suite of JWST capabilities will provide a substantial advance in our understanding of planetary system evolution.

5. Summary

JWST will play a central role, along with other new capabilities such as Herschel, ALMA, and large groundbased telescopes, in advancing our understanding of the four key questions:

How do interstellar clouds of gas and dust begin their collapse into stars?

What processes regulate the star formation following this collapse?

How do planets form in dense disks of gas and dust around young stars?

What is the subsequent evolution of planetary systems?

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