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Understanding Star Formation with the NGST

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Abstract: NGST will be the most sensitive telescope for thermal infrared observations of the heavens when it is launched in mid-2009. Observations in the thermal infrared portion of the spectrum are important for a number of areas in the evolution of young stars: the very early phases of star formation, the dynamic processes related to mass accretion and outflows, the late evolution of protoplanetary disks, the kinematics of deeply embedded clusters and the study of H II and PDR regions in the Local Group. NGST will make contributions to all of these areas, and for some it is likely to be the most important tool for study in the next 15 years.

1. INTRODUCTION

The successor of the Hubble Space Telescope (HST), the Next Generation Space Telescope (NGST), will be a radiatively cooled, $\sim$ 8m aperture infrared optimized telescope providing diffraction-limited imaging at 2μm and sensitivity limited by the zodiacal background at $\lambda < 10\mu$m. Owing to the low-background conditions of its orbit at the Sun-Earth L2 point, NGST will offer a number of unique advantages over any current or planned ground-based facility, despite the enormous revolution taking place in ground-based astronomy. Even with multi-conjugate adaptive optics and laser beacons, the background radiation from the Earth's atmosphere will be sufficiently strong to make the sensitivity of a 30m telescope far worse than a cooled space telescope like NGST.

A key advantage of NGST is the *deep, high spatial resolution imaging capability in the mid-IR* ($\lambda \geq 3\mu$m). NGST will have a nearly 1000× better sensitivity compared to ground-based 8m telescopes at these wavelengths even at fairly high spectral resolution ($\frac{\lambda}{\Delta\lambda} < 10^4$ Gillett & Mountain 1998). NGST will also outperform in the mid-IR future 25 m class telescopes by more than an order of magnitude. Small aperture, LHe cooled space telescopes like SIRTF remain 5 magnitudes above the sensitivity limits of NGST. Moreover, the 10× smaller aperture means a 100× higher sensitivity to source confusion, a crucial limitation especially at low galactic latitudes and in nearby galaxies, the most relevant areas for star formation

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studies. Equipped with detectors able to operate in (natural) background limited conditions, NGST will remain unrivaled longward than $\lambda \sim 3\mu$m.

The mid-IR range is essential for star formation studies. Stars are born in cold, high density cores opaque to the visible and near-IR radiation. Once created, protostars remain surrounded by circumstellar envelopes and disks that emit in the IR the radiation they absorb from the star or, in the case of accreting disks, actively produced through viscous dissipation. In the very early phases, the star formation phenomenon is characterized by the transfer of large amounts of energy and momentum to the interstellar medium (Lada 1985). Under the influence of energetic winds and stellar radiation, the interstellar medium passes through a variety of physical conditions, characterized by shock waves, hypersonic turbulence, and peculiar chemistry that can be traced by a rich combinations of spectroscopic features mostly emitted at mid-IR wavelengths, as recently revealed by the ISO satellite.

We illustrate four key problems in star formation that will benefit from mid-IR observations with NGST. Three major research themes, namely 1) the early phases of star formation; 2) the disk evolution; and 3) the interstellar medium in star forming regions, have also been identified by the NGST Ad-Hoc Science Working Group as important elements of the Design Reference Mission. The related documentation is publicly available at the web site of the Space Telescope Science Institute (`http://www.ngst.stsci.edu/drm/programs.html`).

2. THE EARLY PHASES OF STAR FORMATION

We concentrate on low-mass stars, since they provide the standard paradigm, noting that it has been recently suggested that high mass stars may form by merging of lower-mass cores (Bonnell et al. 1998; Stahler et al. 2000).

2.1 Pre-Protostars

The formation of a single, isolated star begins with a gravitationally bound fragment ("core"), condensed within a molecular cloud from lower density regions due to gravitational (Jeans) instability, or some other external agent. Under the simplest hypothesis (no rotation, no magnetic fields), the core evolves toward a standard configuration, the singular isothermal sphere, characterized by a r^{-2} density law (Chandrasekhar 1967; Shu 1977). This isothermal sphere is a limiting, unstable configuration, because gas having sufficiently low opacity to remain isothermal is unable to support his own gravitational pull through thermal pressure. The sphere collapses from the "inside-out," proceeding faster in the denser central regions and propagating to the outer parts at the sound speed. A hydrostatic protostellar core forms in the center surrounded by free-falling material and an outer, quasi-static envelope i.e. the fossil isothermal sphere not yet reached by the collapse wave. This simplified picture ignores the magnetic energy thought to slow this collapse process to make the cloud collapse times compatible with the observed star formation rates in the Galaxy. Including magnetic fields, the density distribution flattens out toward the center (Mouschovias 1976; Nakano 1984).

Assuming that the presence of a protostellar core can be revealed by its far-IR emission in the IRAS bands, Ward-Thompson et al. (1994) suggested that molecular cores without IRAS sources may be observed in the early free-fall, or "pre-protostellar" phase. They found a number of molecular cores with density profiles less steep than r^{-2}, in good agreement with the magnetic support hypothesis. Recently, Gregersen & Evans (2000) observed the molecular cores of Ward-Thompson et al. in the HCO^{+} J =3–2 line, finding signatures indicating overall infall. New maps with higher spatial resolution obtained at 1.3 mm (Ward-Thompson et al. 1999), show that the molecular cores appear filamentary and/or fragmented. Interestingly, the authors estimate dynamic time-scales longer than the evolutionary time-scales predicted by magnetic support models.

Although NGST cannot observe the very cold ($\sim$ 13K) dust directly, it will be essential to discriminate between pre-protostellar and more evolved sources. This criterion corresponds to that adopted by Ward-Thompson et al. (1994) by using IRAS data, but NGST would guarantee a spatial resolution $\sim$ 1–2 order of magnitudes higher than IRAS or SIRTF.

2.2 Class 0 Protostars

The next important step in the star formation process is the formation of a central hydrostatic core during the collapse. There are in fact two core phases (Larson 1969): the first is when core immediately forms and the central density becomes so high that opacity changes the thermodynamic status from isothermal to adiabatic. Consequently, the temperature rises and the pressure is able to stop the collapse. This neutral, central core in almost hydrostatic equilibrium is continues to receive mass from the outer isothermal envelope, almost in free fall, gaining mass and increasing in temperature. Once it reaches $T \sim 2,000$K, molecular hydrogen dissociation creates an energy sink and a second collapse phase ensues inside the first core, leading to the formation of the second, final protostellar core. As the lifetime of the two cores are in a 1/25 ratio, the first core phase is much more elusive (Boss & Yorke 1995).

Due to the difference in time-scales, the central core(s) forms well before the collapse of the outer envelope. Observationally, this difference means that there are sources in which a central core (typically detected in the far-IR by IRAS) has formed but has not yet accreted most of the envelope (as detected at sub-mm wavelengths). These sources might also be observed in optically thick molecular lines, and they should have the spectroscopic signature of collapse, a blue-shifted peak brighter than the red-shifted peak. Approximately 30 objects of this type have been identified (see André, Motte, & Bacmann 1999). They have been called "Class 0" sources (André, Ward-Thompson, & Barsony 1993). Boss & Yorke (1995) introduced "Class −1" sources to classify those objects in the first, outer core phase. Class 0 (and Class −1) sources show SEDs peaking in the far-IR, resembling a single temperature black body at $T \sim$ 15–30 K. They have typical sizes of $\sim$ 1000AU and are also associated with powerful, collimated molecular outflows, suggesting that mass loss phenomena set very early in the star formation process.

This phase is important because it is in this phase that the final stellar mass is determined. Here NGST can provide unique observational capability. Numerical models indicate that the hot core produces a characteristic signature in the SEDs, namely an IR "warm shoulder" that should be detectable by IRAS and SIRTF (André et al 1993; Boss & Yorke 1995). This hypothesis was confirmed recently by Cernicharo et al. (2000) with an ISO-CAM detection of the mid-IR emission (at 5.3, 6.6 and 6.5μm) from the Class 0 protostar VLA 1 in the HH1–HH2 region in Orion (Fig.1).

The discovery of Cernicharo et al. demonstrates the potential of NGST for these studies. If faint Class 0 sources can be imaged at mid-IR wavelengths with ISO, then NGST ($\sim 0\overset{''}{.}3$ at 10μm, corresponding to $\sim$ 50 AU at 150pc) will resolve the inner envelopes across hundreds of resolution elements, where $A_v \geq 100$. An $1''$ diameter extended source with a 20μm flux of 10μJy would be detected with a S/N=5 in $\approx$ 2.5 hr. NGST could, therefore, survey all known Class −1/0 cores in a few days (see also Barsony & Whitney 2000). Deep high reso-

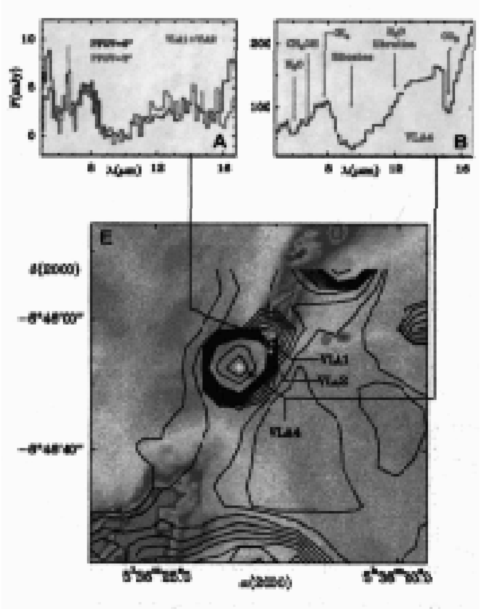

Fig. 1: The IR spectra of the sources VLA1 (Class 0 protostar), VLA2 and VLA4 in the L1641 molecular cloud complex. The map represents the 7μm emission detected by ISOCAM (contour) superimposed on the [SII] 6717/31 Å image (gray scale). (From Cernicharo et al. 2000).

lution imaging would also allow the discovery of multiple sources, getting information on core fragmentation and the formation of multiple systems. Since the first/outer and second/inner cores have different temperatures, they should produce different spectral signatures detectable by NGST. NGST could thus isolate the elusive Class −1 sources. Departures from the spherical symmetry through anisotropic scattering and polarization will tell us how protostellar disks, a natural result from the infall of high-angular momentum material, form and evolve.

3. DYNAMIC PHENOMENA

The basic scenario we have depicted is enriched by a variety of dynamic phenomena. Collapsing material having even a modest amount of angular momentum is unable to fall on the central core but, rather, will spiral down and form a rotationally-supported equatorial disk. Losing angular momentum, the disk material slowly migrates to the inner parts of the disk and is finally accreted on the star. The accretion of material at the star-disk interface is also thought to be responsible for the powerful, highly collimated mass outflows. Outflows from young stellar objects carry away angular momentum and prevent further protostar formation by injecting energy and momentum into the ambient medium.

The simultaneous presence of infall, outflow, rotation and magnetic fields complicates these models. For example, the analysis of the infall just on the basis of spatially unresolved line profiles often provides ambiguous results. Ceccarelli et al. (2000) reconstructed the structure of the collapsing envelope of IRAS16293−2422 down to 30AU using the ratios of H_2O, OI and SiO lines obtained with ISO-LWS, in the range 45μm–200μm. Higher energy transitions of H_2O like the $6_{52} - 5_{23}$ line at 22.62 μm remained undetected by ISO-SWS, but with a 3σ limit corresponding to a few seconds of integration on NGST. NGST has the ability to resolve spatially these tracers of the collapse and therefore yield a complete picture of the dynamical distribution of material. Equipping NGST with a mid-IR high resolution spectrometers, it should be possible to reconstruct the three-dimensional structure of the collapse.

Shock Fronts

Shocks are expected to develop in presence of mass infall/accretion and of mass outflows. The accretion flow impacts the disk rather than the protostellar core. Hydrodynamical two-dimensional calculations including rotation (Yorke, Bodenheimer, & Laughlin 1995; Yorke & Bodenheimer 1999) indicate that the disk is encased in possibly two accretion shock fronts, both resulting primarily from the dissipation of the vertical component of the velocity (Figure 2). In these models, the disk size grows with time due to angular momentum transport, and the positions of the shock fronts change accordingly. The disk shocks will disappear when the envelope accretion terminates, either because the entire envelope has collapsed or because it has been cleared by the mass outflows. In this scenario, we expect to detect disk shocks when the protostellar core has not yet become visible as a near-IR source, and vice versa.

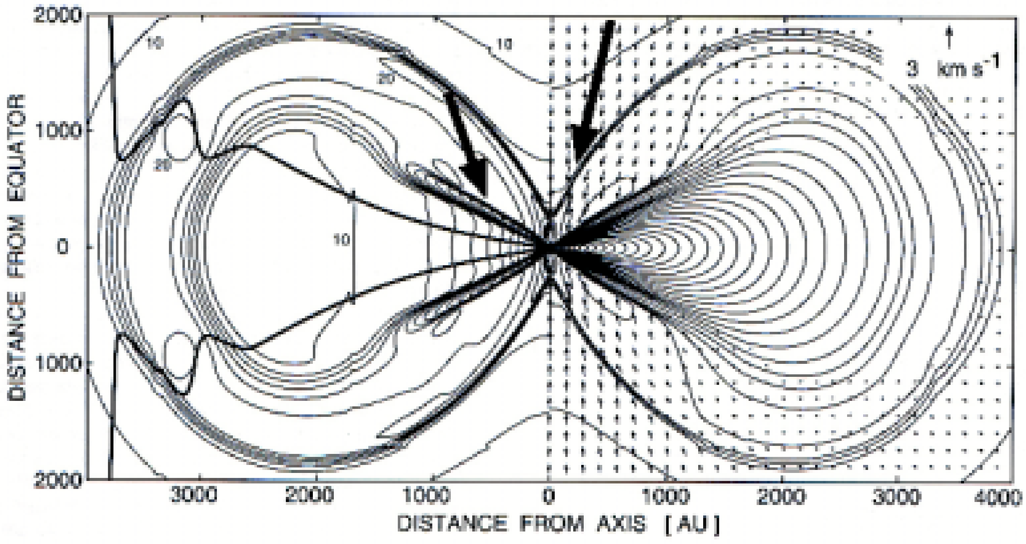

Fig. 2: Gas temperature (left frame), density and velocity (right frame) structure for a protostellar disk accreting envelope material. The thick arrows point to the loci of the accretion shocks (from Yorke & Bodenheimer 1999).

NGST can investigate the accretion/disk interaction by resolving directly the physical extent of the disks in selected shock tracer lines. ISO demonstrated, on the embedded cluster associated with the very luminous protostellar object IRC-2 in Orion, that high-density shocks can produce complex mid-IR spectra (see figure). NGST will produce rich mid-IR spectra of virtually every accreting protostar within ~ 500pc.

Shocks also form at the interface between the envelope and the jet/wind emitted by the central object (stellar jets, Herbig-Haro objects). The origin of the outflows is still an open problem. Studying the Class 0 protostar IRAM 04191+1523, André et al. (1999) have shown that a well-developed bipolar flow can be generated in absence of a sizeable accretion disk, indicating that the driving mechanism must be localized in the innermost, compact accretion disk. NGST will uncover the mass-loss history of the central source by imaging the youngest jets still embedded in the parental envelope. The $\Delta v = 0$ rotational lines of the H_2 molecule are sensitive shock indicators for the low energy ($v \simeq 5$km s^{-1}) excitation distributed in the mid-IR spectrum.

4. PRE-MAIN-SEQUENCE STARS AND PROTOPLANETARY DISKS

The star formation process continues with the young stars slowly dissipating their placental envelope and circumstellar disks. The emitted spectra change as the stars evolve. An empirical classification of objects in Classes I, II, and III has been widely used to describe the spectral energy distributions in these phases (Lada 1987). Class I objects have assembled most of their stellar mass, have envelopes less massive than the central core, and are surrounded by massive accreting disks. Class II objects have cleared their envelopes but show conspicuous IR excess emission from the circumstellar disk, possibly still accreting. Low mass objects in this phase correspond to the classical T Tauri stars. Class III sources are surrounded by a residual optically thin disk and possibly host newly formed planetary systems.

The IR emission at these later stages is dominated by the disks. Since the central star has already accreted the bulk of its mass, circumstellar disks may be considered in the "protoplanetary" rather than the "protostellar" phase. When the disks are optically thin (e.g. at millimeter wavelengths), their mass and density distributions can be inferred from observation (Beckwith et al. 1990). However, planets are assembled in the disk's inner regions, unresolved by millimeter telescopes. At the shortest wavelengths (2–10μm), disks are usually optically thick, and the extraction of the basic physical parameters becomes strongly model dependent. When the inner disk finally dissipates and the dust becomes optically thin, the emission falls quickly below the current detection limits. Statistical studies over large samples of sources allow us to compensate for the model uncertainties (e.g. the disk tilt angle) and can provide information about properties such as the evolutionary time scales.

For example, data taken with the ISO satellite show that the dust component in the terrestrial planet region disappears on timescales $\sim$ 10Myr, comparable to the cessation of accretion (Robberto et al. 1999). Statistical studies will be boosted by SIRTF, and at the time NGST will be launched our understanding of the disk evolution and dissipation, at least from the statistical point of view, should be significantly improved. Many questions will remain open, such as the evolution of the gaseous (molecular) component, the grain growth, the presence of voids or resonances in the density distribution, and the presence, structure and composition of Oort clouds, to name a few. Possible contributions of NGST to these questions are illustrated in the NGST Design Reference Mission, and we point the reader to the proposal of M. Meyer et al. for further details.

5. YOUNG CLUSTER DYNAMICS

The NGST high-resolution capabilities, together with the long-term stability of the PSF, will provide very accurate positions of YSOs deeply embedded in the parental molecular clouds. NGST will be able to catch them before they have moved significantly relative to one another. Moreover, proper motions will be available after a few years of these measurement. A 5 km s^{-1} tangential velocity gives a 1 mas/year proper motion at 1 kpc. Sampling with 0.1 arcsec/pixel, this accuracy corresponds to a displacement of 1/100 pixel, well within the limits of standard astrometric techniques. These measurements, coupled with radial velocity estimates, will allow us to study the three dimensional kinematics of young stellar clusters. From the positions and proper motions, we should be able to solve the crucial problem of the mechanism(s) triggering star-formation.

5.1 STRUCTURE OF H II AND PDR REGIONS

Massive stars dominate the return of mass and energy from the young stellar component of the Galaxy to the interstellar medium. They produce ionizing radiation, molecular outflows, stellar winds, and eventually supernovae. The ionizing radiation creates HII regions that emit a wealth of diagnostic fine structure lines at mid-IR wavelengths and may be used to obtain the gas density (from different lines of the same ion, e.g. [SII] 18.7μm/33.5μm) or the ionization status (from different ions of the same element, e.g. [NeII]12.8μm/[NeIII]15.6μm). HII regions are surrounded by Photo-Dissociation Regions (PDRs), in which the molecular gas is exposed to far ultraviolet (6–13.6 eV) radiation. The cooling in PDRs occurs primarily via H_2 as well as CO, H_2O and OH. PAH emission is also considered a tracer of PDRs, as the small dust grains are destroyed inside the HII regions.

Figure 3 shows the complex interplay between HII regions and PDRs. The Galactic star-forming region NGC6334 has been imaged recently from the South Pole with the SPIREX experiment (Burton et al. 2000). The filamentary emission of PAH emission, observed at 3.3 μm, follows the edges of the HII regions, traced by the Brα line at 4.05μm. The shell structures of $\sim$ 1–1.5pc surround compact HII regions which are about 0.2–0.3 pc in size. These observations are extremely difficult from the ground and will not be possible with SIRTF, as IRAC is not equipped with narrow band filters. NGST on the other hand is well suited to this kind of observation and will readily provide similar images in diagnostic lines for every major star formation region up to the distance of the Magellanic clouds and beyond.

6. CONCLUSION

NGST will offer a unique combination of angular resolution, sensitivity and wide field capability enabling a number of studies of key problems in star formation otherwise impossible with any current or planned facility. The mid-IR regime is essential for the solution of these problems, and we have illustrated a number of areas where NGST should make the most important contributions.

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Fig. 3: Multi-color image of NGC 6334 at a distance of 1.7 kpc taken with the 60 cm SPIREX telescope. Blue: 3.3μm (PAH); green: 3.5μm (-band); red: 4.0μm (Br-α). The field of view is $\sim 20' \times 20'$, corresponding to 10pc$\times$10pc

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