Observing Star and Planet Formation in the Submillimeter and Far Infrared

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Abstract. Stars form in the densest parts of cold interstellar clouds which — due to presence of obscuring dust — cannot be observed with optical telescopes. Recent rapid progress in understanding how stars and planets are formed has gone hand in hand with our ability to observe extremely young systems in the infrared and (sub-)millimeter spectral regimes. The detections and silhouetted imaging of disks around young objects in the visible and NIR have demonstrated the common occurrence of circumstellar disks and their associated jets and outflows in star forming regions. However, in order to obtain quantitative information pertaining to even earlier evolutionary phases, studies at longer wavelengths are necessary. From spectro-photometric imaging at all wavelengths we learn about the temperature and density structure of the young stellar environment. From narrow band imaging in the far infrared and submillimeter spectral regimes we can learn much about the velocity structure and the chemical makeup (pre-biotic material) of the planet-forming regions.

1. Introduction

Stars are the basic building blocks of larger scale structures in the visible universe. Their birth, aging and deaths affect the evolution of their host galaxies in a multitude of ways which make them key players in the universe's evolution. Understanding the formation of stars and planets and their early evolution is a necessary prerequisite for understanding the cycles of matter in the universe and the sequence of events which has led to the origin of life on Earth.

Some of the key issues that need to be addressed are:

- Formation of the first stars in the early universe and their evolution
  - How and when did the first stars form?
  - What is the subsequent star formation history?
  - Is there an unknown population of high-z IR galaxies?

- Formation of stars and the physics of the interstellar medium
  - How do stars form out of the interstellar medium?
  - Circulation / enrichment / chemical processes of the interstellar medium
  - Detailed studies of nearby (resolvable) protostars, star forming regions, "mini-starbursts", starbursts — each as templates

- Formation of new solar systems in protostellar disks
  - How are planetisimals built up out of interstellar dust?

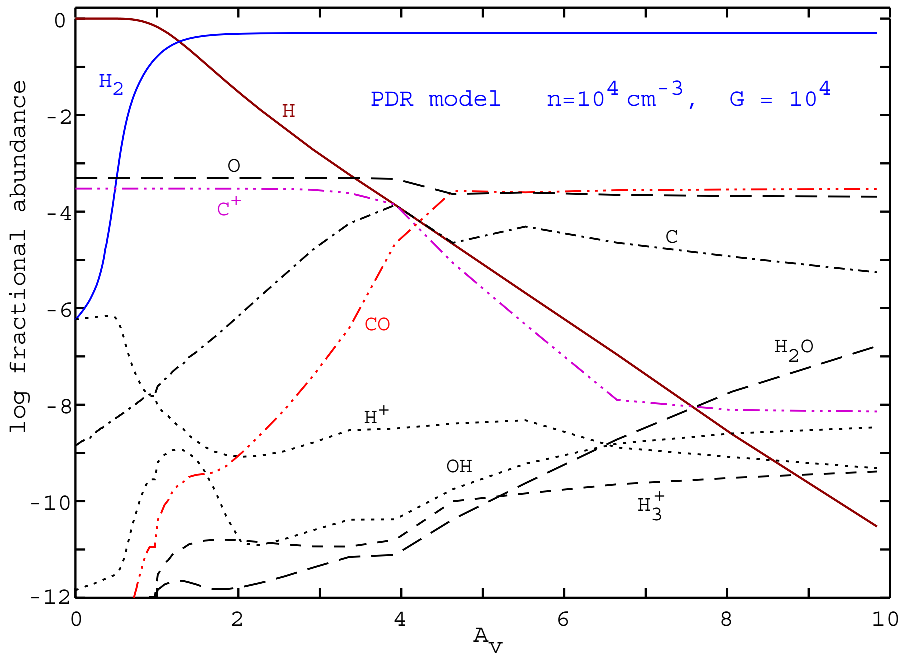

Figure 1. Example of chemical structure within a constant density "Photodissociated Region".

– What is the chemical state (pre-biotic?) of material that enters into planetary atmospheres?

- Cometary, planetary, and satellite bodies and atmospheres
  – History of the solar system, pristine material in comets
  – Minor bodies in the solar system

Theoretical studies of the formation of circumstellar disks via infall and their early evolution stress their importance not only as a reservoir of material to be partially accreted onto the (proto-)stellar cores and partially ejected in a collimated outflow, but as the basic environment for the growth and evolution of dust grains and ultimately for the formation of planetesimals and planets. Presumably many of the building blocks of pre-biotic chemistry, large organic molecules, are either created in this gaseous environment and subsequently adsorbed onto solid particles or are formed directly on the surfaces of the solid material.

Newly formed massive stars illuminate and begin to modify their immediate environment in a manner that is observable as the "PDR" phenomenon (see Fig. 1). Analysis of low excitation fine structure lines of these PDRs supplies vital quantitative information on global star formation in extragalactic sources (c.f. Table 1 and Figs. 2 and 3). The careful interpretation of observations of PDRs on a much smaller scale — protostellar disks being photoionized and UV-photoheated by a nearby hot star — give us quantitative information on the structure and evolution of these disks (see Fig. 4).

Further progress in our understanding of star formation is inhibited by our *inability* to make high spectrally resolved and high spatially resolved images of young objects during early evolutionary phases. The warm material in disks, infall regions, and jets cools predominantly through low excitation fine structure lines and molecular rotational transitions, many

Table 1. Bridging the gap from local high mass star formation to Starburst Galaxies

Object	Distance	# of OB stars	Spatial scale
Orion	0.5 kpc	4	0.001pc
NGC3603	7 kpc	10's	0.015pc
30 Dor	55 kpc	100s	0.1pc
NGC248	2 Mpc	1000's	4pc
Z=1	4 Gpc	10,000's	8 kpc

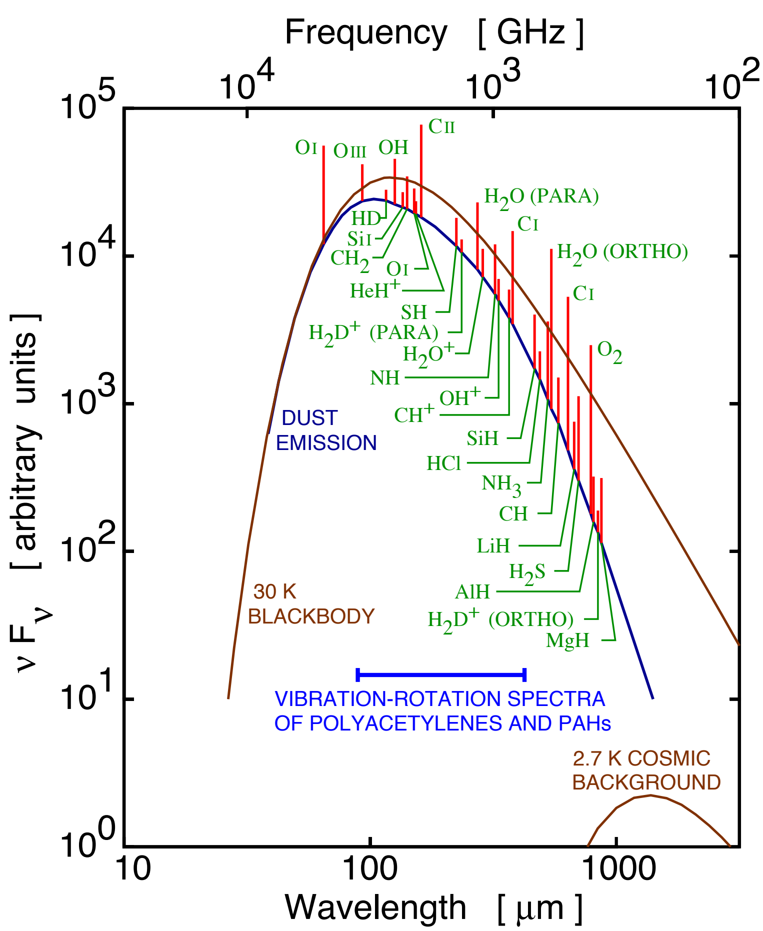

Figure 2. Schematic spectrum of a star forming region which is generally dominated by the far infrared continuum emission of dust and line emission from fine structure transitions, molecules, and dust spectral feature.

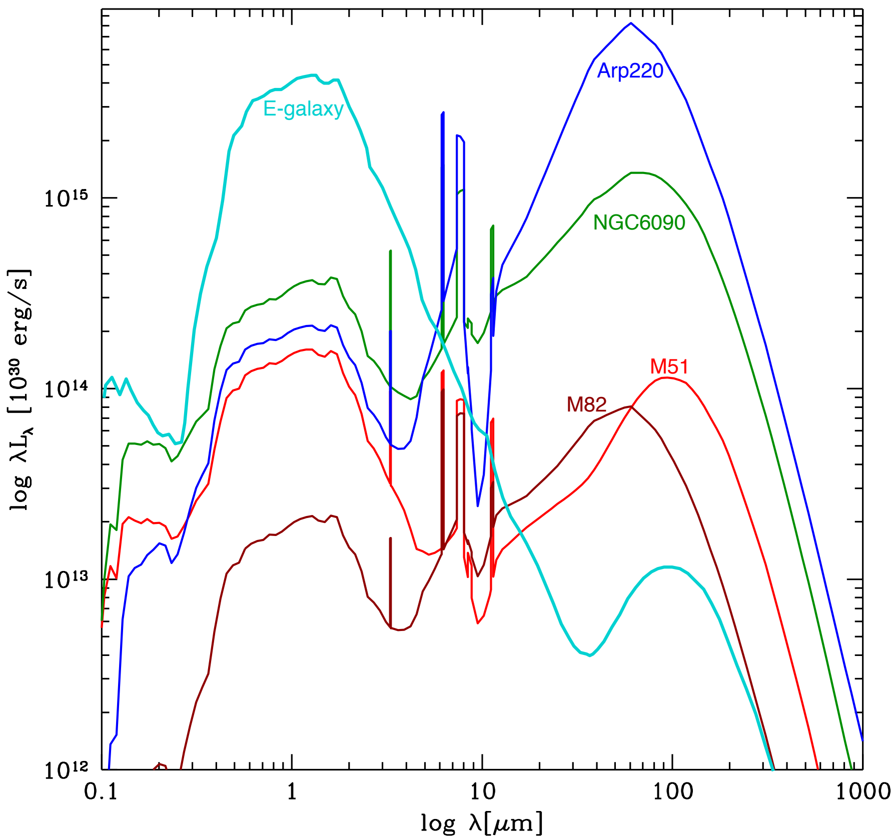

Figure 3. Spectra of galaxies experiencing differing rates of star formation activity (adapted from Silva et al., 1998). Note that the ratio of UV+optical+near-infrared to far-infrared emission can vary by many orders of magnitude. Estimates of the total luminosity of a galaxy which do not include the far infrared are highly unreliable.

atmospherically blocked, as well as dust continuum emission in the FIR and submillimeter spectral regimes. High quality observations in this wavelength range in conjunction with detailed modeling can provide unique insights into the distributions of temperature, density, velocity, chemical composition, dust composition and ionization state during various phases of star and planet formation. The complexity of the lines of H_2O as observed with ISO in star forming regions (c.f. Fig. 5) and how they change strongly from position to position provide a compelling argument for improved spatial resolution.

The interactions of the (proto-)stars, possible close companions, mass infall, disks, jets and interstellar material in their close vicinity guarantee the occurrence of structure over a wide spectrum of spatial scales. Using the values (sensitivity, spectral and spatial resolution) believed attainable for space-based FIR/submillimeter interferometers within 10 years, the

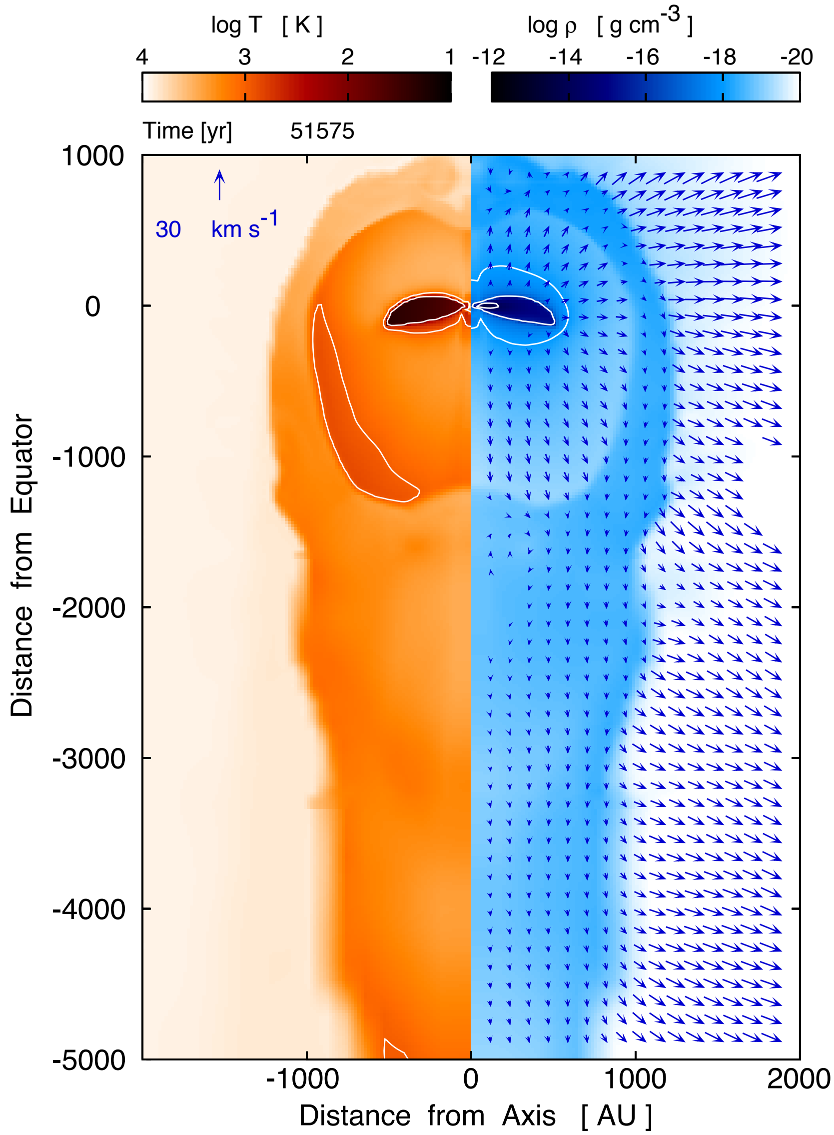

Figure 4. Temperature (left), density, and velocity structure (right) of a protostellar disk undergoing photoevaporation by an O5 star located 0.5 pc "above" the disks central star at (0,0). The vertical "z" axis is assumed to be an axis of rotational symmetry (adapted from Richling & Yorke 2000

outer regions of post-planet forming debris disks will be observable down to 1 "zodi"[1] — complimenting what can be done with TPF at shorter wavelengths in regards to the inner disk regions. Jupiter and possibly Saturn would be observable around stars out to 15 pc, perhaps their associated gaps as well. During earlier phases, jets, infall motions and disk accretion shocks are clearly detectable. With interferometric studies of proper motions (30 km s^{-1}= 1 mas per week at 130 pc) these flows and structures can be traced as they evolve over the course of weeks.

When discussing the mission capabilities which would be highly advantageous for these types of observations, it is important to note 1) there is a continuous improvement in the quality of science which can be done by improving sensitivity as well as angular/spectral resolution, 2) there are important "quantum leaps" in the types of problems which can be addressed and 3) any improvement by orders of magnitude in sensitivity and angular/spectral resolution has the potential of yielding unexpected significant discoveries. We can address points 1) and 2), but by definition can say little about point 3).

With even better spectral resolution the identification of individual complex organic species such as the Polycyclic Aromatic Hydrocarbons (PAHs) is possible. The quality of science attainable is not limited by this particular choice spatial resolution either. With increasing spatial resolution it eventually will be possible to image directly the jet formation and innermost collimation zones — indeed, protostellar jets provide us with the nearest examples of this generic phenomenon generally occurring in accretion disks. Thus by extension we will learn about the jet mechanisms in more distant active galactic nuclei and black holes.

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References

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[1] One "zodi" corresponds to the emission of interplanetary dust in our own Solar System

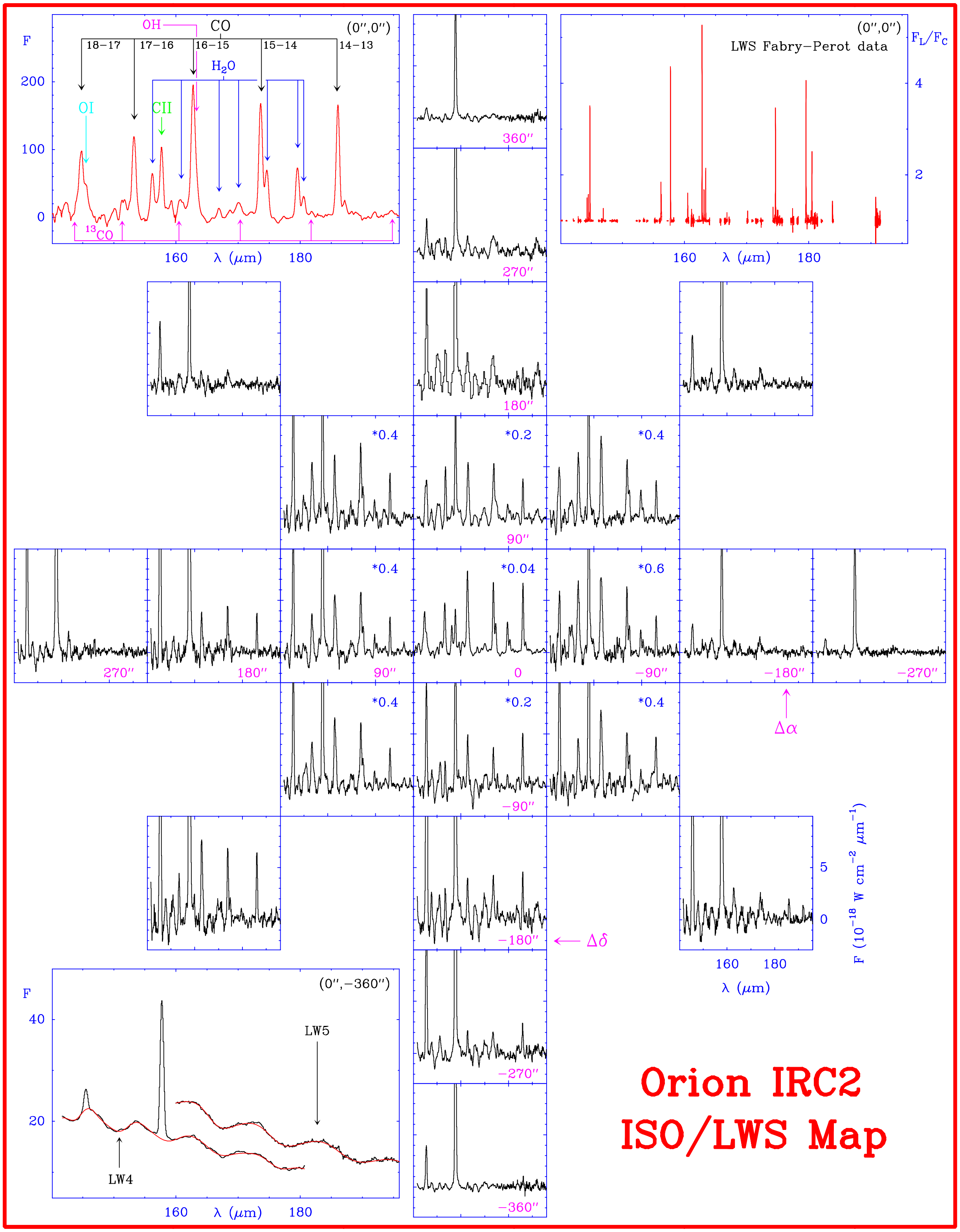

Figure 5. H_2O emission in the Orion region