The Institute of Space and Astronautical Science
Report SP No.14, December 2000

The Interstellar Medium in the Mid- and Far-infrared

By

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(November 1, 2000)

Abstract: The mid-infrared and far-infrared regions of the electromagnetic spectrum contain a rich assortment of spectral features which can be used as tracers of the physical properties of interstellar and circumstellar material. In the broadest sense, these features include the thermal blackbody emission from dust grains at a variety of temperatures, solid state vibrational modes in the refractory and icy components of dust grains, vibrational spectra of "large" molecules such as polycyclic aromatic hydrocarbons (PAHs), vibrational and rotational bands of simple molecules, atomic recombination lines in the lighter atoms, and fine-structure transitions in heavier atoms and ions. The spectroscopic possibilities in the infrared increase still further if highly red-shifted features from shorter wavelength regimes are considered. In the following, the types of spectroscopic observations enabled by access to mid- and far-infrared (here, roughly 5 μm to 30 μm, and 30 μm to 1 mm, respectively) spectra are briefly summarized.

1. INTRODUCTION

Although large parts of the infrared spectrum are inaccessible to study from the ground due to the high atmospheric opacity within absorption bands of common atmospheric constituents, a very impressive range of infrared spectroscopy has already been carried out successfully, either by means of the few available high-quality atmospheric transmission windows, or from observing platforms at high altitudes, such as airborne observatories and balloons, or from infrared space telescopes (e.g. Haas, Davidson & Erickson 1994; Bicay et al. 1999; Cox & Kessler 1999). Ground-based observations have necessarily been limited to the brighter objects because of signal-to-noise limitations imposed by thermal emission from the atmosphere and the telescope optics, but on the other hand, such observations have the great advantages of high angular resolution and easy access. In the other case, at high altitudes and from space, the dominant limitation has been the low angular resolutions attainable with small apertures, so that spatial information is sacrificed. Large-aperture space-borne infrared telescopes such as FIRST, HII/L2, and NGST thus have the potential to provide the best of both worlds: high sensitivity coupled with high angular resolution.

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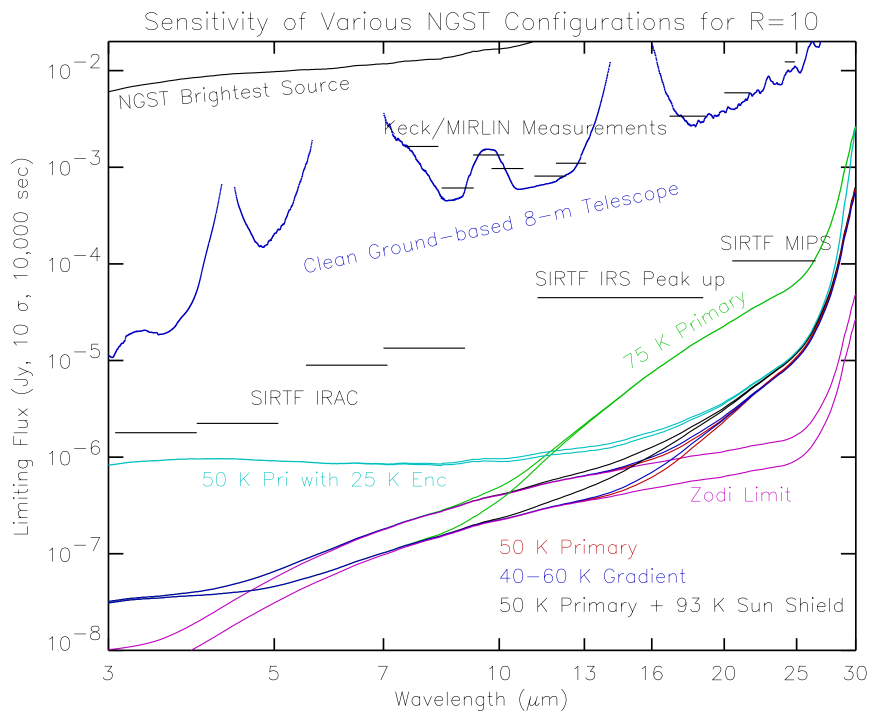

Fig. 1: Sensitivity curves and saturation fluxes for a mid-infrared NGST, for a spectral resolving power equal to 10. The different curves show the contributions of various elements to the background noise. The top curve shows the detector saturation level. NGST has the potential to be at least 3 orders of magnitude more sensitive than ground-based telescopes, and 1 to 2 orders of magnitude more sensitive than SIRTF.

As a result, entirely new classes of science become possible, as illustrated dramatically in Smith & Koratkar (1998), Swings (1998), Cox & Kessler (1999), Smith & Long (2000) and these proceedings. As an example, the fantastic sensitivities achievable with a mid-infrared capability on NGST can be seen in Figures 1 and 2. Such a three order-of-magnitude sensitivity increase compared to ground-based facilities will enable, among other things, extremely sensitive surveys for obscured star-formation sites in the early universe, identification of stellar populations at early epochs by means of their redshifted spectra, studies of the interstellar medium in galactic and nuclear contexts out to high redshifts, characterization of the life-cycle of dust grains from their generation in evolved-star outflows to their incorporation into the accretion process around newly forming stars in molecular clouds, observations of the evolution of deeply-embedded protostars and dusty accretion disks, and very sensitive searches for brown dwarfs and exoplanets, followed by spectroscopic characterization.

In such a brief paper, these numerous topics cannot be explored with any degree of completeness, so the focus here is on a simple summary of the spectroscopic tools available in the infrared. For more detailed summaries of the astronomical possibilities, the reader is referred to the conference proceedings listed in the references, and to the NGST instrument study website, http://wwwmipd.gsfc.nasa.gov/isim/science.htm.

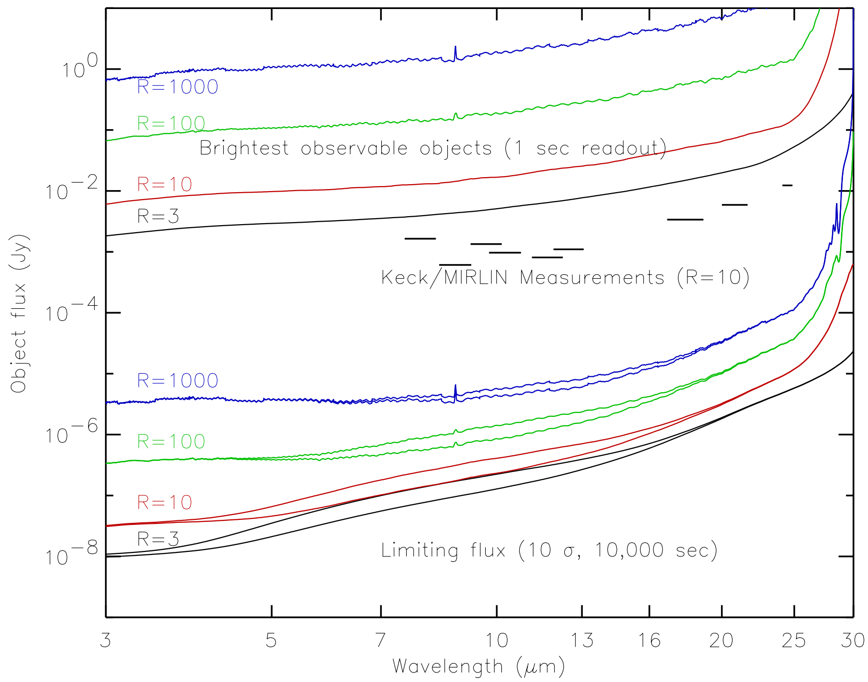

Fig. 2: Sensitivity curves and saturation fluxes for a mid-infrared NGST, for a range of spectral resolving powers.

2. INFRARED SPECTROSCOPY

2.1 Atomic Lines

In common with the optical and radio regimes, two general classes of spectroscopic lines from neutral and ionized atoms are available in the infrared: recombination lines in highly-excited light atoms, and fine-structure transitions in heavier atoms. However, important differences between these wavelength regimes exist.

First, the lower levels, n, of the infrared recombination lines in neutral Hydrogen cover the middle range of roughly n = 5 to 25, and thus lie between the highly excited levels seen in the radio regime, and the deepest lower-levels seen in the optical regime (note that this characterization refers solely to the excitation of the lower level, and not to the transition energy, for which the characterization would be the reverse). This excitation difference has already proven useful in studies of the millimeter-wave hydrogen maser source in the circumstellar disk around MWC349: while the millimeter and far-infrared lines mase, the near-infrared lines do not, so that the transition from inversion to thermal excitation occurs in the mid-infrared (Thum et al. 1998). A second difference arises in regard to recombination lines in elements heavier than Hydrogen: in the radio and/or optical regimes, it is possible to observe recombination lines of a few of the heavier elements, such as He and C. In the infrared, available sensitivities to date have been insufficient to study these lines.

As to fine-structure lines, those available in the mid- and far-infrared are generally ground-term fine-structure transitions, i.e., simple spin-flip transitions with no orbital angular momentum change involved. Because the ground-term fine-structure line transition frequencies depend on the local electric field strength at the position of the unpaired electron, in general the emission frequencies tend to increase with atomic number. Thus the C, N and O ionic fine-structure lines lie in the far-infrared, the lines from the somewhat heavier Ne, Si, S and Ar ions tend to fall in the mid-infrared, while Fe lines are seen in the near-infrared. (Note that the 21 cm spin-flip transition of atomic Hydrogen, which is also nominally in accord with this trend, is in fact a magnetic hyperfine transition, involving electron spin - nuclear spin coupling rather than spin-orbit coupling). Thus the mid- and far-infrared provide important probes of elemental abundances and excitations of the elements in the first two rows of the periodic table. Because of the low extinction at infrared wavelengths, such spectroscopy is particularly important for deeply embedded sources, and so such spectroscopy has proven itself particularly adept at identifying buried energy sources in heavily-extincted galactic nuclei (Moorwood 1999).

Of equal importance, several neutral atoms with unpaired electrons, i.e., C, O, Si and S, also have infrared fine-structure transitions. Thus abundances and excitations in neutral regions can also be probed. These fine-structure lines are therefore particularly important for investigations of structure and chemistry in PDRs (photodissociation regions), as complements to the molecular probes used at radio and millimeter wavelengths (Draine & Bertoldi 1999).

2.2 Molecules

In terms of molecules, there is no doubt that the singular contribution which mid-infrared spectroscopy can provide is in the measurement of the rotational transitions of molecular H_2 and HD. Because of the low mass of the H_2 molecule, its lowest rotational transition is at 28 μm (Figure 3, van Dishoeck 2000). H_2 is of course the dominant constituent of molecular clouds, but it is difficult to observe because its lack of a dipole moment means that only quadrupole transitions are possible. While the lowest transition (2–0) at 28 μm is not accessible from the ground, the next three rotational H_2 lines are (e.g. Parmar, Lacy, & Achtermann 1994). The mid-infrared is thus a crucial regime for obtaining information on the warm medium in which H_2 can be seen in emission. This molecule is quite prominent in molecular outflows, and so these lines (along with far-infrared CO lines) allow the different temperature regimes in interstellar shocks to be probed, both in star-formation sites and in supernovae (Cox & Kessler 1999).

In addition, the far-infrared is also home to the lowest or near-lowest rotational transitions of several light hydride molecules and radicals such as HeH^+, LiH, CH, CH^+, OH, OH^+, H_2O, H_3O^+, NH, NH^+, NH_2, NH_3, HF, HCl, SiH, SH, and H_2S, and several somewhat heavier, non-hydride, molecules such as CO, H_2CO, SO and SO_2. Several of these species are very important in a number of ways, as the list includes several fundamental chemical building blocks in molecular clouds, dominant coolants, tracers of ionization fraction, abundance tracers, and, if deuterated isotopes are included, tracers of deuterium fractionation.

The mid-infrared, on the other hand, is home to the lowest vibrational excitations of simple molecules, such as CH_4, C_2H_2, CO_2, HCN, NH_3, H_2O, and C_6H_6. Mid-infrared observations of several of these molecules are particularly important both because of their high abundances, and more importantly, because their symmetry prevents the existence of rotational dipole transitions for e.g., CH_4, C_2H_2, CO_2, and C_6H_6. For observations of the high redshift universe, the mid-infrared acquires added importance, as it becomes the new home of the very important H_2 and CO vibrational bands (with rest frame wavelengths near 2 μm).

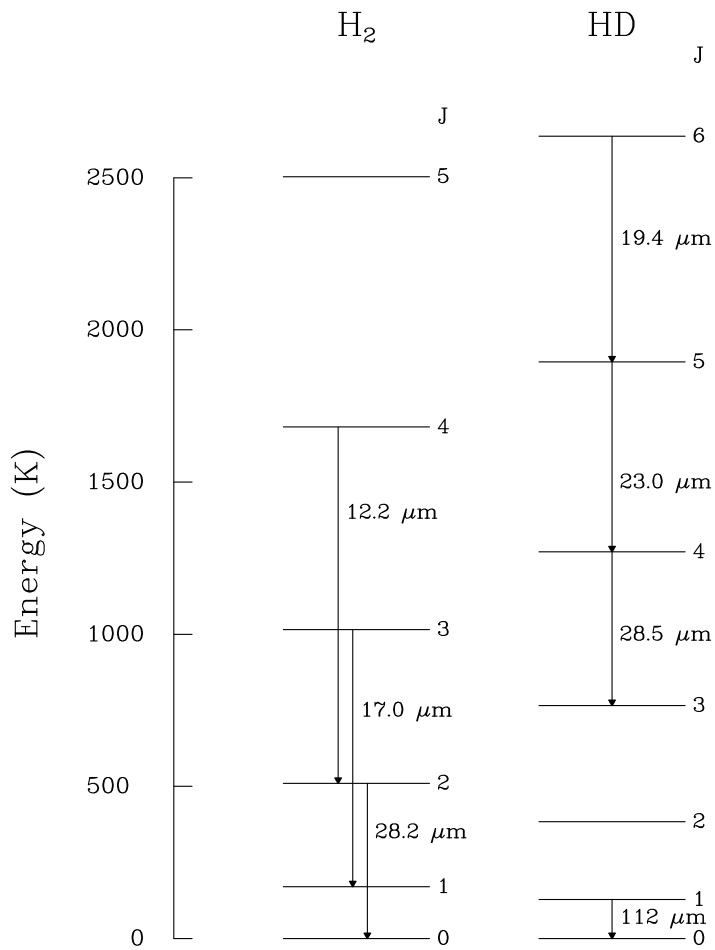

Fig. 3: Energy level diagrams for the H_2 and HD molecules, with the lowest few transitions labeled.

2.3 Dust and PAHs

Finally, the solid component of the interstellar medium, as well as the transitional case of "large molecules" or clusters, is best probed in the mid-infrared. Given recent ISO results (Cox & Kessler 1999), it is clear that this will be a very important field for future followup studies. In particular, high spatial resolution studies will be critical to defining the full life-cycle of dust grains in the interstellar medium, from their generation and ejection in evolved stars, to their time spent in the diffuse interstellar medium, where optical/UV illumination can modify their structure, to their incorporation into cold molecular clouds, where they can acquire icy mantles, to their settling into dense molecular cloud cores, where the condensation of gases begins to take effect, to their processing in accretion disks, where optical/UV illumination and shocks may free grain mantles, to their incorporation into planet-forming disks, in which radial segregation of ices and rocky constituents takes effect and the gas phase disappears, and finally to the debris disk phase, in which planet formation is largely complete, but residual reservoirs of icy and rocky grains exist. Many of these effects require both the mid-infrared waveband to see the relevant spectral features, and high angular resolution to determine radial distributions and evolutions. Especially intriguing is the observation of silicates in both amorphous and crystalline forms (Waelkens et al. 1996), thus providing clues to the processing history of the grain material, and the ability of mid-infrared measurements to simultaneously provide information on both the gas and ice phases of the volatile gases with mid-infrared vibrational bands (Boogert 1999). The specific spectral features available generally fall into the categories of silicates (amorphous and crystalline), oxides (and sulfides), PAHs and ices, and a recent line list is given in van Dishoek (2000)

3. CONCLUSIONS

In summary, the potential of infrared spectroscopy is immense. In particular, high spatial and spectral resolution studies of the solid phase, and of symmetric molecules, in interstellar and circumstellar material can only be carried out in the mid-infrared. Observations of dusty disks around protostars, young stars, and middle-aged stars such as our own will be able to track the process by which accretion disks evolve from their nascent phase into the debris disks such as our own star's zodiacal cloud. The evolution of dust grains can also be traced from their origin in the ejecta of evolved stars to their incorporation in molecular clouds and accretion disks. The spectroscopy of obscured star-formation sites at high redshift will provide crucial information on the earliest phases of star formation and galaxy assembly. Finally, spectral studies of brown dwarfs and exoplanets will allow their internal structure to be probed.

Perhaps most intriguing of all is the potential of the mid-infrared in the search for habitable planets and life. Combined with a technique to suppress starlight, the well known mid-infrared bands of H_2O, O_3, CO_2 and CH_4 present in our own atmosphere can be used to test for the presence of an atmosphere such as is found on our own solar system's rocky planets (CO_2), the presence in the atmosphere of water, and the presence of non-equilibrium (life-related ?) chemistry (O_3 and CH_4). Such studies must no doubt await the advent of mid-infrared interferometry in space, such as is proposed for NASA's Terrestrial Planet Finder mission (Beichman, Wolfe, & Lindensmith 1999). Nevertheless, it is clear that the mid-infrared and far-infrared spectral regions are vital to an increasing number of planned and proposed space missions from many nations.

ACKNOWLEDGMENT

I wish to thank the workshop organizers for their invitation and their hospitality, as well as for their patience in awaiting this contribution. The research described herein was carried out at JPL under a contract with NASA.

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