REVIEW OF THE WORKSHOP

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ABSTRACT

This workshop has highlighted the importance of an interplay between observations, laboratory simulations, theoretical modeling, and instrument characterization. When all these aspects of research are carefully combined, new interpretations emerge to provide unforeseen astrophysical insight.

1. LABORATORY FITS TO ASTRONOMICAL SPECTRA

For the past several decades, laboratory astrophysicists, notably Mayo Greenberg in Leiden, were conducting experiments to obtain infrared spectra of likely interstellar constituents at low temperatures. We noted their work but largely lacked the ability to surmount the atmosphere to obtain the necessary unobstructed spectra that could have been matched to laboratory data.

With ISO, all this has changed. At this meeting we saw beautifully clear spectra of interstellar ices of water vapor H_2O, methane CH_4, formaldehyde H_2CO, carbon monoxide CO, and carbon dioxide CO_2, both in the prevalent form $^{12}CO_2$ and in its minor isotopic form $^{13}CO_2$. Spectral shapes showed mixtures of these species in both polar and apolar ices –signifying an embedding in a matrix rich, respectively, in H_2O or CO_2. Pascale Ehrenfreund also pointed out an important missing ingredient. We have not observed significant levels of admixed solid O_2 in these ices. This is puzzling, as I will note below.

Ices are useful indicators of the temperatures of the star-forming regions in which they are observed. CO and O_2 ices sublime at an astrophysically significant rate at roughly 20 - 25K. This is appreciably lower than the sublimation temperatures of CO_2 or H_2O, that lie, respectively, in the range of 55 - 80K and 100 - 150K. Chris Wright showed us spectra of several regions containing young stellar objects. In some, CO appeared fully frozen; in others partially frozen with some addition of gas; and finally, in still others, in fully gaseous form.

Molecular ices found on interstellar grains are likely to be deposits formed when stray atoms are frozen out on a grain and then combine to form molecules. Low-temperature laboratory samples of molecules ion-irradiated with 30 to 60 keV argon ions show spectra that significantly differ from spectra of the same substances before irradiation. Giovanni Strazzulla suggested that processing material this way in the laboratory may not only better simulate interstellar cosmic ray irradiation of grain material, but also dissociate deposited materials and allow them to recombine in ways that more accurately reflect the chemical processing that takes place on interstellar grains.

To date, laboratory astrophysicists have largely worked with materials more or less deposited in bulk on cryogenically cooled surfaces. Yet, we know that the diffuse interstellar features originate in grains that might be aggregates of no more than $\sim$ 100 atoms. In recent years, however, studies of the properties of atoms such as sodium in clusters numbering about a hundred atoms, have revealed new physical characteristics that differ from bulk properties of the same atoms. Surface effects become important, bond angles change. We may, therefore, expect that the spectra of small aggregates of interstellar atoms and molecules might substantially differ from bulk spectra obtained in the laboratory. Though technically difficult, it should be fruitful to investigate laboratory spectra of small aggregates of atoms, molecules, and perhaps admixtures of ions, that are likely to be important interstellar constituents.

While such considerations are important, there is no doubt that even the bulk properties of different minerals catalogued to date already yield striking results. Louis d'Hendecourt showed us a laboratory spectrum of the magnesium rich olivine mineral forsterite from 10 to 40 μm, and its excellent fit to the dust spectrum of comet Hale-Bopp, again illustrating the usefulness of a broad compendium of spectra of widely differing molecular and mineral species. As Jacques Crovisier then added, the superposed 2.7μm H_2O water vapor ν_3 bands yield an ortho-para ratio of $\sim$ 2.45 for this comet, suggesting equilibration at a temperature of 25K, corresponding to a distance of order 100 AU from the sun.

2. THEORETICAL FITS TO ASTRONOMICAL SPECTRA

This brings up a second point that clearly emerged at this meeting. Theorists, who for decades have been predicting the shapes of infrared spectra expected from a wide variety of astronomical sources, now are also suddenly able to verify the great power of their techniques. Therèse Encrenaz showed us a model spectrum of Saturn that included phosphene PH_3, arsene AsH_3, ammonia NH_3, deuterated methane CH_3D, and a slight trace of water vapor H_2O. Were it not for the spectacularly good fit that all the other constituents provide to the spectrum of Saturn observed with ISO across the entire near and mid-infrared, the small differences made by the traces of water vapor would never have been noticed. Thanks to the theoretical fits, however, H_2O is clearly detected. We are now asking whether the water originates in infall of material from the Saturnian rings or possibly signifies other sources.

Excellent theoretical fits were also evident in the simulation of stars with static atmospheres. Such model atmospheres require detailed understanding of the spectral frequencies and transition probabilities of huge lists of spectral lines of atoms, radicals, molecules, their isotopes, and their ions. Robert Kurucz told us he uses 58 million lines to fit his model atmospheres. In turn, Christoffel Waelkens showed us how essential high-quality fits are for precise calibrations of ISO's short wavelength spectrometer, SWS.

3. THE IMPORTANCE OF CALIBRATIONS FOR UNDERSTANDING STARS

Just as comprehensive stellar models are essential for calibrating the ISO instruments, so also are reliable calibrations essential for understanding the spectra of stars with dynamic atmospheres. Josef Hron and Bernhard Aringer showed us how difficult it is to account for the atmospheres of Asymptotic Giant Branch (AGB) stars, where theoretical models would require a detailed understanding of the properties of dust, stellar pulsations, winds, mass loss, and shocks. Here, well-calibrated spectra from ISO are in strong demand for more sophisticated atmospheric modeling.

Takashi Onaka showed us spectra and photometric observations of two oxygen-rich Mira variables obtained over an entire cycle of light variations. A great deal of work remains to be done before we fully understand these complex stars. Their mass loss rates remain uncertain by at least an order of magnitude, and these loss rates will need to be understood if we are to determine the relative extent to which variable stars, as contrasted to novae and supernovae, enrich the interstellar medium with heavy nuclear species. ISO's spectral resolution may not suffice to provide all the information that will ultimately be needed to fully model atmospheric dynamics, wind velocities at different distances from the star, the chemical species at these distances, the radial distances at which dust grains first nucleate, and the rates at which grains subsequently grow, but data obtained to date are already providing new insights.

4. CHEMICAL PROCESSING

Just as modeling of stellar atmospheres is important, we are also beginning to pursue models of interstellar clouds. We need to gain a better understanding of chemical processes and the spectra that would identify them as interstellar clouds collapse, are shocked, form new molecular species, or are lit up by the formation of a new star. We can test such models of chemical networks against spectra ISO is now providing.

A most useful tool for studying a variety of gaseous domains is the CLOUDY program of Gary Ferland. His collaborator, Peter van Hoof, displayed how this program facilitates the study of photodissociation regions (PDRs)and starburst galaxies. Both Frank Bertoldi and Pierre Cox showed us the information that now can be derived for PDRs. In particular, a large number of rovibrational emission lines of molecular hydrogen H_2 are clearly discerned. If we select only the rotational transitions of the ground vibrational state, we can plot the excitation energy of a given rotational state J against observed column densities $N(J)$ divided by statistical weight $g(J) = n(2J + 1)$. Here $n = 3$ for ortho and 1 for para states, respectively the odd and even angular momentum states including $J = 0$. The slopes of these plots for the PDRs in S140 and NGC 7023 reveal surprisingly high temperatures, respectively, 500 and 580K.

In the planetary nebular NGC 7027 Xiaowei Liu showed us spectral features of CH^+ that he, José Cernicharo and coworkers had identified. Once again, long-available laboratory spectra permitted this identification. Unidentified lines in this and other planetary nebulae, however, persist and may arise from unknown molecular species.

A poster by Paolo Saraceno and coworkers showed water vapor emission to be unexpectedly low in shocked interstellar regions. They found water vapor cooling to be typically an order of magnitude or more lower than cooling through CO transitions. Saraceno feels that water vapor may be under abundant in these regions. If so, this raises another problem. In the sun oxygen is roughly twice as abundant as carbon. We speak of a cosmic abundance of oxygen which is roughly twice that of carbon. In interstellar clouds the abundance of oxygen appears to be anomalously low. By now we have the ability to observe oxygen in its atomic form and as OH, as H_2O ice and vapor, as CO, and as CO_2. Carbon is present in atomic form and as CO, CO_2, CH_4 and larger organic molecules, and perhaps as graphite in grains. This makes it difficult to see an abundance of oxygen that might still be twice as high as that of carbon, unless oxygen was present in molecular form, O_2. But this may already be ruled out by the apparent absence of solid O_2 in ices. Laboratory spectra of ices consisting of H_2O, CO, and CO_2 show changes in shape when O_2 is admixed. Pascale Ehrenfreund told us that such features are not found in the spectra of interstellar ices, suggesting that O_2 is not a significant component. Searches with ISO for gaseous O_2 are also being carried out. It will be interesting to see what they will teach us. Molecular oxygen is difficult to observe because of its symmetric dipole structure, and we may not be able to put significant upper limits on its abundance. The interstellar abundance of oxygen is one of the log-standing problems of interstellar chemistry that ISO may still have an opportunity to clarify.

5. GALAXIES

The ratio of interstellar N^{++}/O^{++} as a function of distance from the Galaxy's center was originally studied from the KAO. By extending such studies across the Galaxy and looking at both the Large and Small Magellanic Clouds, Jean-Paul Baluteau found a decreasing nitrogen-to-oxygen ratio at increasing distances from the Galactic Center. This decline continues as we go to the LMC and SMC. Studies of this kind should permit us to obtain greater insight on the chemical evolution of galaxies on time scales of billions of years.

A considerable body of work on active galactic nuclei (AGNs) and starburst galaxies has been carried out. Dieter Lutz showed us that the archetypical ultraluminous galaxy Arp 220 has a [NeII]/[OIV] ratio more similar to starbursts than to AGNs. In contrast to these two near infrared lines seen in emission, Jacqueline Fischer showed us a long wavelength spectrum of molecular lines all of which are seen in absorption. The sole emission line in the far infrared appeared to be [CII] at 158 μm. Her spectra would lead one to conclude that enormous opacities exist surrounding the sources of heating and a mid-infrared optical depth of order 20 at the wavelengths of [NeII] and [OIV]. It is difficult to explain how these lines can be seen strongly in emission while the [CII] line, which lies at much longer wavelengths where opacities are low, is so weak.

An equally difficult question to answer is why ultraluminous galaxies should in the first place contain so much dust when they appear to be merely two ordinary colliding galaxies? Where does all the dust come from? How is it distributed around the star forming regions? Where does it lie in relation to the molecular constituents?

There is much to learn.

6. ISO AS AN OBSERVATORY

This workshop has shown the power of a single instrument, intensely studied to properly characterize all its features, and used by a large number of observers all sharing information to perfect the characterization. It has shown the importance of the stability of conditions in space, and of systematic, periodic updates of calibrations and the tracking of slowly varying instrumental characteristics. The process is not yet complete. A great deal of additional information about the detectors, telescope and their properties remains to be extracted before we are all done. But the possibility of learning from each other as we begin to better understand our data and the instruments that obtained them, will yield a far richer lode of interpretable observations than if we were individually trying to use some arbitrary telescope.

This cooperative attitude is responsible for much of the observatory's success. We owe the Instrument Teams, the Instrument Data teams, and the operations specialists a great debt of thanks for their hard work on the community's behalf.

All of us also wish to thank Martin Kessler for organizing this workshop, and the entire staff at Villa Franca for mounting such a well organized, outstandingly interesting meeting for the broad research community.

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