NEW EXPERIMENTAL POSSIBILITIES AND THE FUTURE AT FAR IR WAVELENGTHS

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ABSTRACT

The observation of molecular phenomena in interstellar clouds by spectroscopy in the longer wavelength region of the infrared is discussed. This is a region where sensitivity is almost universally affected by background continua, appropriate techniques may be either coherent or incoherent, and work above most of the atmosphere is required for much of the spectral range. So far, only a very limited amount of molecular work has been done in the far-infrared, but one can expect fairly rapid growth and important results.

The infrared region from a few microns to about one millimeter is full of molecular frequencies and, from the point of view of astronomy, is relatively unexploited. While the microwave region contains a large fraction of the lowest rotational transitions of molecules, the submillimeter range includes the low rotational states of simple hydrides and many higher rotational states of heavier molecules. The medium infrared is, of course, characteristic of the rotation-vibration spectra, which extend between about 2 and 50 microns. Rather hot objects, such as stellar atmospheres or shocked interstellar gases, are needed to excite spectra in the shorter wavelength infrared range. However, the molecules themselves need not necessarily be so hot, since absorption spectra can be observed against a hot continuum. In addition, warm interstellar gas of temperatures in the range of 50 to 100K can excite the far-infrared, in particular rotational transitions of light molecules in the region 50 to 500 microns. So far, a modest number of molecular transitions have been studied in the 10 micron atmospheric window and at shorter wavelengths, and at longer wavelengths a very few lines have been studied in the submillimeter range from platforms above most of the atmosphere. Clearly, there remains to be obtained from the infrared region a great deal of information about interstellar molecules which is of a different nature and complimentary to what we already know from microwave work.

There are, of course, technical difficulties which have heretofore impeded progress. One is the lack of atmospheric transparency except

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for windows at certain well-known wavelength regions. This may be obviated by airplane, balloon, and satellite work. Another has been the lack of sensitive detectors. Recently the required detector developments have been getting under way and there is already some success. A third and major difficulty is the competing background radiation from all that is around us. At wavelengths longer than about 10 microns, apparatus such as spectrometers, lenses, and telescopes at room temperature emit quanta copiously, and so also does the atmosphere. Detection of astronomically interesting radiation must at times be achieved in the presence of a background which is as much as 10^6 times greater than the radiation being detected. While microwave astronomy has some problems with background radiation, infrared astronomy faces much more severe ones.

Since my colleague Don Hall has discussed the shorter IR region, I shall concentrate attention on the longer wavelength range, where background radiation from objects at normal temperature is omni-present and dictates the experimental techniques which can be successful. In this region, the background radiation is proportional to bandwidth, and hence it is important to use spectral resolution which is as fine as the line widths to be detected in order to obtain the best discrimination between lines and background. This is true not only because of interfering background from our apparatus on the Earth, but also in many cases from interfering continuum of the astronomical objects themselves.

Ideally, if the background is completely constant, noise is usually proportional to the square root of the number of quanta received and in this case a Fourier transform spectrometer would be exactly as sensitive as a very narrow bandpass spectrometer which is swept in frequency over the same range of the spectrum which might be observed by Fourier transform techniques. In actuality, the noise is not of this character. There are systematic fluctuations in background, for example, time or spatial variations in the temperature of the sky or of the telescope being used, which produce excess noise and which dominate if the bandwidth is large. Hence in high backgrounds, Fourier transform spectroscopy, which is so generally valuable in the shorter infrared region, cannot usefully be employed with its full potential bandwidth. A narrow band system may itself use Fourier transform spectroscopy with a narrow band filter, or it may be simply a very narrow band monochromator which is swept in frequency just enough to cover a line or a few lines which are to be observed. Thus gratings and Fabry-Perot systems are frequently favored.

Background radiation in the short infrared region gives fluctuations which are proportional to the square root of the total number of photons, $\sqrt{n}$, or to the square root of the power incident on the detector. In the microwave region, where Bose-Einstein condensation of photons is prominent, the noise fluctuations are directly porportional to incident power, being given, for example, by $kT \sqrt{\Delta\nu}$. The far-infrared is in the transition region between these, and an exact calculation of quantum noise fluctuations needs to come from a more general expression. Since this transition behavior is not commonly treated, it is discussed in Appendix I. Usually, near the transition region an estimate from either a $\sqrt{n}$ or kT $\sqrt{\Delta\nu}$ type of approximation is not far wrong.

Bolometers were the detectors which opened up infrared astronomy. However, they are primarily useful for broadband detection and will probably not be very widely used in the future for molecular spectroscopy. Fortunately quantum detectors, photoconductors, and photodiodes have now been developed with good quantum efficiency for selected spectral regions varying from the shortest infrared wavelengths to those as long as about 150 microns. Under favorable conditions, these provide little excess noise above the fundamental quantum noise of the background photons which strike them.

At the longer wavelengths, heterodyne detection is a favorable technique, particularly for high spectral resolution. Of course, for wavelengths longer than one millimeter it is almost universally used. For wavelengths slightly shorter than one millimeter a variety of nonlinear elements are used as mixers, including Schottky diodes and other devices common at longer wavelengths. Phillips' interesting hot electron heterodyne system is quite successful in this wavelength range, though its bandwidth is narrower than is desired. Superconducting devices, including superconducting amplifiers, are being developed and already are useful in limited ways. In the shorter wavelength range, from about 100 microns to the shorter infrared, photoconductors and photodiodes allow the possibility of good quality heterodyne detection. A moderate amount of heterodyne molecular spectorscopy has been done in the 10 micron region, as reported here by Betz, and this general style of spectroscopy should be useful for the study of stellar atmospheres at wavelengths as short as four to five microns. In the 100 micron region, there is as yet no very good heterodyne detection system. However, there are promising methods which are being explored, and perhaps good heterodyne detection in this region is not very far off. If it can be achieved, it can be expected to replace direct detection by photoconductors and photodiodes, even though these are relatively successful.

Principles required for sensitive spectroscopy in the longer wavelength infrared may be illustrated by the schematic in Figure 1 of a 100 micron spectrometer built at Berkeley, primarily by Storey and Watson, and used in NASA's Kuiper Observatory. The instrument involves a fixed Fabry-Perot interferometer in tandem with a tunable or variable Fabry-Perot. Plates of these Fabry-Perots are made of fine metal mesh appropriate to a wavelength of about 100 microns. The entire interior of the spectrometer is cooled, so that radiation reaching the detector is essentially limited to that seen by the instrument through the telescope within the narrow band representing the resolution of the instrument. While the variable or tunable Fabry-Perot illustrated in the figure is not at low temperature,

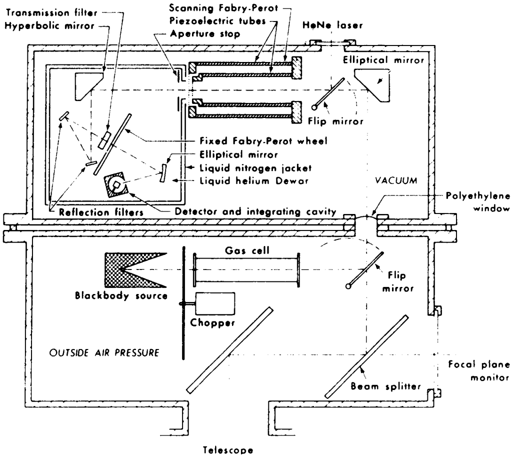


Figure 1: Schematic of the Berkeley cooled-optics, narrow band spectrometer for the 100 micron region, built by J.Storey and D.Watson

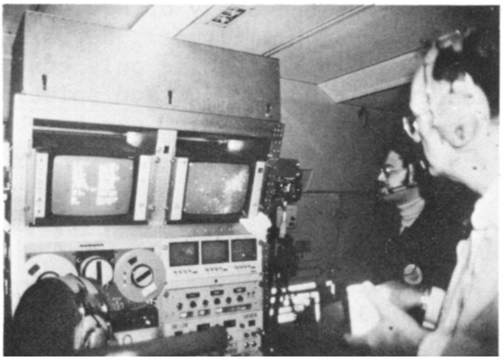
it is a good reflector at all wavelengths except those which are transmitted, and hence appears to be cool so far as radiation seen by the detector is concerned. This spectrometer has a limiting resolving power of about 5000, which corresponds approximately to the broader molecular features in interstellar clouds. It would be desirable to have still somewhat higher resolution. On the other hand, the spectrometer is very effective and I believe adequately sensitive to detect a number of molecular lines in warm clouds.

For the present, no molecular spectra have been detected from interstellar clouds between the near submillimeter range and the 10 micron window. In atmospheric windows at 10 micron wavelengths and shorter, photoconductive and photodiode detectors have successfully detected a variety of molecules in circumstellar materials, as well as CO and hydrogen in a few special interstellar regions. The Fourier transform system of Hall and Ridgeway has, for example, been quite successful at the shorter IR wavelengths. Ten micron heterodyne spectroscopy has successfully detected a number of molecular lines in circumstellar material, although not yet directly in interstellar clouds. Heterodyne detection working in the submillimeter range has been used successfully from the ground to detect a number of molecular lines, for example the second and third transitions of CO. A limited but valuable program of submillimeter heterodyne observations has been carried out in NASA's high flying C141 airplane by Phillips and his associates.

While work so far has been rather limited, it seems inevitable that the infrared, particularly the far-infrared which has not yet been properly exploited, will provide a great deal of valuable information about interstellar clouds. The high rotational transitions of simple linear molecules such as CO should reveal much about the

Figure 2: NASA's Kuiper Astronomical Observatory. A 36" telescope looks through the rectangular hole in the upper left side of the fuselage of a C141 airplane.

Figure 3: Interior of the Kuiper Astronomical Observatory, showing a star field being tracked and presentation of observatory parameters.



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cooling of clouds and the excitation of molecules. The lower rotational transitions of hydrides, including HD, should be detectable in the far-infrared. At the moment, with microwaves we usually measure so few molecular parameters that we can generally successfully fit observations to broad and simple models of clouds. Undoubtedly, as additional transitions in the far-infrared are measured the situation will in many cases appear more complicated and more difficult to fit with simple models, but at least we should be closer to an accurate view of cloud behavior. The mid and far infrared have already produced a good deal of valuable information from observations of the fine structure of ions,and as the far-infrared begins to detect molecular transitions as well, it should be especially valuable in understanding the warmer regions in clouds and the interfaces between ionized and molecular regions.

Where will far-infrared astronomy be done? Certainly at dry sites. These will include the best dry sites presently known for observations from the ground, and also observations above the atmosphere. Already some spectroscopy has been done from balloons, incidental to the study of the short wavelength end of the isotropic radiation. More has been done from NASA's Gerard Kuiper Observatory, a C141 outfitted with a 36" telescope which looks directly out of the side of the airplane. The C141 Observatory with an opening for the 36" telescope is illustrated in Figure 2 and its interior in Figure 3. The latter figure shows the shirt-sleeve environment in which crew and astronomers work, and an oscilloscope display of the star field used both for finding and for some forms of tracking. In the longer run, infrared spectral observations should be made from satellites, particulary for the study of H_2O, which still shows intense absorption lines even at high altitude. So far, plans for satellite observations of the far-infrared involve only continuum measurements, but in time the additional sensitivity and pointing precision and the freedom from absorption lines which can be obtained from satellites should play an important role in molecular observations.

Appendix I

The theoretical sensitivity of a system using a photodiode detector and limited only by photon noise is given by an NEP (signal power equal to noise with 1 Hz post-detection bandwidth) as follows:

$$\mathrm{NEP} = \frac{1}{1-\varepsilon}\sqrt{\frac{2P_B h\nu}{\eta}\left(\frac{P_B\lambda^2\eta}{2h\nu A\Omega\Delta\nu} + 1\right)}\Big/\sqrt{\mathrm{Hz}} \qquad (1)$$

where $h\nu$ is the quantal energy, λ the wavelength, P_B the continuum power falling on the detector, η the detector's quantum efficiency, $A\Omega\Delta\nu$ respectively the area, solid angle, and bandwidth accepted by the detector, and ε the fractional transmission loss in the optical path from source to detector. The quantity $\frac{2A\Omega\Delta\nu}{\lambda^2}$ is simply the number m of propagation modes (spatial, polarization, and temporal), accepted by the detector and the 1 Hz bandwidth. Hence $n = \frac{P_B \lambda^2 \eta}{2h\nu A\Omega\Delta\nu}$ is the number of photoelectrons produced per mode.

If n>>1, (1) becomes $\mathrm{NEP}_{n>>1} = \frac{\sqrt{2}\,P_B}{\sqrt{m}(1-\varepsilon)}$.

For the case of a diffraction limited telescope and a single polarization, $\frac{2A\Omega}{\lambda^2}$ is unity and one has $\mathrm{NEP}_{n>>1} = \frac{\sqrt{2}kT_B\sqrt{\Delta\nu}}{1-\varepsilon}$. This corresponds to the familiar noise power of $kT_B\sqrt{\Delta\nu}$ for a one second average, where T_B is the effective temperature of the incident radiation. It is the appropriate form in the microwave region where Bose-Einstein condensation is important, and the NEP is independent of quantum efficiency as long as η is large enough so that n>>1.

If n<<1, (1) becomes

$$\mathrm{NEP}_{n<<1} = \frac{1}{1-\varepsilon}\sqrt{\frac{2P_B h\nu}{\eta}} = \frac{h\nu}{1-\varepsilon}\sqrt{\frac{2P_B}{\eta h\nu}}\,,$$

which is a familiar form for short wavelengths where photons are individually countable, since $\frac{P_B}{h\nu}$ is the total number of photons/sec. In this case, the quantum efficiency η is quite important.

Another form of expression (1) can be useful in the infrared. If the background radiation power P_B comes from a warm, partially transmitting optical path of temperature T, one has

$$\mathrm{NEP} = \frac{2h\nu}{1-\varepsilon}\sqrt{\frac{A\Omega\Delta\nu\varepsilon/\eta}{\lambda^2\left(e^{\frac{h\nu}{kT}}-1\right)}}\sqrt{\frac{e^{\frac{h\nu}{kT}}-1+\varepsilon\eta}{e^{\frac{h\nu}{kT}}-1}}\Big/\sqrt{\mathrm{Hz}} \qquad (2)$$

where ε is the fractional loss in the warm optical path, or $\varepsilon = 1 - e^{-\tau}$ where τ is the optical depth. This form assumes there are no other losses in the system. It applies, as does (1), for the general case independent of the occurrence of Bose-Einstein condensation.

If a photoconductive detector is used rather than a photodiode, there are noise fluctuations due to electron recombination as well as generation, and all of the above expressions must be multiplied by $\sqrt{2}$. If beam chopping is used, the effective NEP is multiplied further by a factor of 2.

DISCUSSION FOLLOWING TOWNES

Snyder: Can you comment on the apparent absence of hydrides?

Townes: Of course, the hydrides of C, O, and N have been detected in the microwave region. Other hydrides, such as metal hydrides, have not yet been found, but I expect that, as soon as good detection of far-infrared molecular lines is possible, hydrides will be among the molecules found. We hope on our next flight to concentrate on and detect molecular lines in the 100μ region.

Goldsmith: What is the resolution of the 100μ spectrometer system?

Townes: We have used it with frequency resolutions between about 0.15 cm^{-1} and 0.05 cm^{-1}. The limiting resolution without further modification is about 0.02 cm^{-1}.

Thaddeus: Do plans exist to search for the fundamental rotational line of HD at 112 microns? It appears to be our best hope of directly observing molecular hydrogen in fairly cool molecular clouds.

Townes: Yes. We have in fact already searched for the 112μm line of HD, but with mediocre sensitivity which provided an upper limit of modest significance. We are hoping to improve the sensitivity of our equipment in a winter flight, and estimates indicate that the line should be detected, at least in the warmer clouds. There is little hope of finding this line, I believe, in the very cool clouds.

Churchwell: Have you been able to detect the OIII 88μm or 52μm lines in the galactic center? If so, is the intensity much lower than in local HII regions?

Townes: We detected the 52μm OIII line from the galactic center. It is far weaker than in most HII regions. This result is consistent with our previously reported low intensity for ArIII and SIV radiation, and implies that there is a cool ionizing source at the galactic center. The 88μm OIII line was not detected; we have only a low upper limit.

Wynn-Williams: How big an advantage would a cooled space-borne telescope give you for molecular infrared spectroscopy?

Townes: A cooled space-borne spectroscope could essentially eliminate background continuum radiation, and, in principle, gain some orders of magnitude in sensitivity. The gain would not be so great, however, for lines from warm clouds where there would be background noise due to the continuum radiation from the clouds themselves. In such cases the increase in sensitivity would be limited to perhaps one order of magnitude. The amount of gain would depend also, of course, on the resolution.

Drapatz: Experiment proposals from German scientists concerning infrared research on Spacelab were combined to form the "German Infra-Red Laboratory" (GIRL), a superfluid helium-cooled telescope (40 cm diameter) with five focal-plane instruments. The instrument, which will also be used for observations of interstellar molecules, is a Michelson interferometer ($\lambda \gtrsim 20$ m, resolution $\sim$0.05 cm^{-1}, field of view 30 - 300 arcmin, limiting sensitivity $\sim 10^{-19}$W cm^{-2} $line^{-1}$ in 10^3 sec integration time). The project was approved in 1978, and the first flight is planned for 1984. More details can be found in the proceedings of the SPIE, Electro-Optical Technical Symposium & Workshop, Huntsville, 1979.