INFRARED STUDIES OF STAR-FORMING REGIONS - SUMMARY

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When Gareth Wynn-Williams first asked me to give this summary talk he specifically requested that I be "provocative." Having already been to Hawaii three times I realized how much easier it is to be laid back rather than provocative here - indeed, I but rarely rise above the ground energy state. So, the prospect of giving this talk has so terrified me that I have been sitting in the front row taking notes for two days now - something I have never done at any meeting. I even sought out the advice of an expert summarizer and first row sitter, my colleague Virginia Trimble, who advised me not to worry, but to simply "tell them what they should have said but didn't."

Well, fortunately, I need not have worried so much since there have been a remarkable number of exciting new results on star formation presented at this meeting. Indeed in order to remember one as interesting I must go back over five years to the meeting that Peter Mezger organized at an Austrian ski resort in January 1975. Many of my friends and colleagues who are here today were also at that meeting. I can still remember, as if it were only yesterday, sitting at a table with Eric Becklin and Nick Scoville and watching, with amazement, the amount of German beer they could consume at a single sitting.

Since it is impossible to review everything of the last two days in fifteen minutes my remarks will be limited to three areas: (1) the largest scale - galactic structure; (2) the intermediate scale - giant molecular clouds; and (3) the small scale - protostars and protoplanets.

In his beautiful paper, Reinhard Genzel much too modestly called the measurement of the distance to Orion by measurement of the proper motions in the H_2O masers a "minor sidelight." His group has also measured the distance to W51 in the same way. This represents a potential breakthrough in our ability to determine the spiral structure of the Milky Way.

We live in a spiral galaxy, but what does it look like? The HI and CO pictures are still quite controversial. Does the CO show spiral

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structure? Maps of extragalactic CO, although helpful, can never entirely solve this problem for our own galaxy. We must find a method for determining distances in the Milky Way that is independent of kinematics. Optical wavelengths are out because of extinction due to the interstellar dust. Radio astronomers have no "standard candles" but the H_2O maser technique seems promising if we can measure the proper motions of many maser spot groups throughout the Milky Way. Improvements in VLBI sensitivities and the passage of time are both required, so this is a difficult experiment.

I have long believed that measuring the galactic distance scale is the birthright of infrared astronomers (perhaps my colleague at Maryland, Frank Kerr, has helped to prejudice me here). They must search for standard infrared candles in the galactic plane at large distances from the Earth. Bob McLaren mentioned to me a few weeks ago that he is planning to study Cepheids in the infrared. This welcome step should help to improve the extragalactic distance scale but won't do much for galactic astronomy. Perhaps IRAS or some other upcoming satellite will detect many infrared sources that ground based astronomers, by measurement of the Brackett lines, can establish to be main-sequence early B and late O-type stars located at large distances from the Earth.

The challenge to infrared astronomers is to find a standard candle before the radio astronomers are able to use the H_2O masers to map out the arms of the Milky Way.

Ultimately, distances will be measured by interplanetary interferometry. Even here infrared astronomers have a fundamental advantage. A recently proposed giant space interferometer (Buyakas et al., 1979) consisting of individual telescopes a few kilometers in size separated by 10 Astronomical Units can, in principle, achieve an angular resolution of 10^{-10} arc seconds at 1-mm wavelength. In practice, scattering by interstellar and interplanetary plasma irregularities may prevent us from reaching this limit. Since this effect varies as λ^2 the best angular resolution will be achieved in the infrared. (Again, optical observations will be limited by interstellar dust.)

The second topic that I would like to discuss are the giant molecular clouds (GMC's). Radio astronomers have discovered GMC's and have shown that there is a problem in understanding their kinematics and long term stability. We have been searching for years for a solution without any resounding successes by studying things such as "clumping." I believe that we can study clumping until the cows come home without really solving the problem. I think that the solution to the mystery probably lies in infrared observations and their interpretation but infrared astronomers must search harder and over larger areas. Perhaps IRAS will do some of the work, for example at 20 μm, as mentioned by Neal Evans in his talk.

To indicate more precisely what I have in mind, I would like to mention two models for GMC's that have recently been proposed. I emphasize that it is entirely possible that neither of these models supplies the correct explanation for the supersonic velocities observed in GMC's but they do illustrate the kinds of infrared observations that might be usefully attempted.

The first model is due to Norman and Silk (1980) who suggest that molecular clouds contain numerous hidden, embedded T Tauri-like stars which possess very energetic winds (of the type that I discuss below in conjunction with Table 1) that stir up the clouds. There are at least two potential problems with this model - the T Tauri stars may not exist in the requisite numbers and, even if they do, they may not possess energetic winds. A second model for supplying large amounts of energy of bulk motion to the GMC's is due to Bash et al. (1980), who propose that as GMC's orbit in the galaxy they are struck by numerous smaller molecular clouds. This model also has some potential problems which I will not discuss here.

At any rate, models such as these can be checked by a variety of infrared observations. The embedded stars will appear as continuum sources. The energetic winds and cloud-cloud collisions will produce shock waves which will heat the gas. This should result in far infrared atomic and molecular line emission of the type observed near HII regions by the Cornell and Berkeley groups. Hill and Hollenbach (1978) have considered the propagation of a 10 km/s shock in a dense cloud. When T has fallen to 100 K behind the shock, far infrared lines from species such as OI, CII, CI, CO, OH may be observable with sensitivities attainable during the 1980's.

It is conceivable that bulk motions in GMC's may be coupled to and controlled by embedded magnetic fields. If so, it may be very difficult to detect the fields at either radio or infrared wavelengths. Polarization measurements in the far infrared may be of some help.

In the past two days we have heard a fantastic array of new material related to the formation of stars, especially in the Kleinmann-Low/Becklin-Neugebauer region in Orion. I long for the simple, "good old days" at the Austrian ski resort where I could relax and drink beer and pretend that I understood Orion.

Probably the most exciting current problem is understanding the physical mechanism responsible for the high-velocity, high-energy phenomena seen by infrared and radio spectroscopists in Orion and other regions of star formation. In the most extreme regions the energy in bulk motions is a few percent of the energy in radiation.

The underlying physical mechanism responsible for this mass motion is still obscure. Indeed the only mention of physical mechanisms at this meeting was the brief exchange between Drs. Beckwith and Beckman regarding radiation pressure driven winds. Dr. Beckman informs me that he has a paper in press in MNRAS on this topic. But radiation driven winds are very controversial as the explanation of the pre-main sequence phenomena listed in Table 1 and other mechanisms that rely on conversion of rotational, pulsational, magnetic, or gravitational energy into kinetic energy of mass outflow deserve consideration. SS433 may indicate that such conversions are possible. Presently unknown factors, such as whether the underlying protostar is single or multiple, may enter into the solution.

At any rate, there now exists a tremendous opportunity for infrared theoreticians and observers to work together to elucidate the fundamental underlying mechanism(s). This certainly does not mean that we should stop gathering new data on the high energy protostellar phenomena but only that the time may already be ripe for some clever intuitive calculations and inspired guesses as to fundamental mechanisms.

To help, I would like to present a Table, a version of which I first showed at a review talk on Orion at the Mexico City AAS meeting in January 1979. A similar table also appears in a paper submitted to the Ap. J. by the Kuipers and me. But first it is necessary to define a quantity I call "Over Pressure" (O.P.): O.P. $\equiv (\dot{M}V_\infty)/(L/c)$. For mass loss driven by radiation pressure, $\dot{M}V_\infty = \tau L/c$. Here $\dot{M}$ is the rate of mass lost, V_∞ is the terminal velocity of the flow, L is the underlying source luminosity, and τ is the effective optical depth for coupling this luminosity to the expanding gas (and dust) cloud. If most of the underlying luminosity escapes without being either scattered or absorbed by the gas and dust then $\tau << 1$. If the radiation suffers multiple absorptions and scatterings before it escapes, then $\tau > 1$.

TABLE 1.

OVER PRESSURES

OBJECT	$L/L_\odot$	A_V(Mag)	O.P.
Main Sequence O-Type Star	10^5	0	~ 1
Infrared Giants (IRC+10216)	10^4	~ 15	~ 1
Planetary Nebulae	10^4	Moderate	~ 1
T Tauri	20	Moderate	
Optical lines			~ 20(?)
2 μm H_2 Emission			25
Herbig Haro Objects	10-1000	$\gtrsim 20$(?)	
Shock Models, Bullet Models			10^2-10^3
2 μm H_2 Emission			$\gtrsim 10^2$(?)
Orion, DR21, etc.	10^5	20-2000(??)	
2 μm H_2 Emission			10^2-10^3

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As an example, consider a planetary nebula for which the following parameters probably apply: $\dot{M} \sim 10^{-5}\ M_{\odot}$/year, $V_{\infty} \sim 20$ km/s, $L \sim 10^{4}\ L_{\odot}$. Then, as indicated in Table 1, O.P. ~ 1. Other assumed values for $\dot{M}$ and V_{∞} may be found in Kuiper et al. (1980). The basic problem is to explain the large over pressures indicated for the pre-main sequence objects.

The over pressure given for T Tauri based on optical data is due to the classical interpretation of Kuhi. This interpretation, strong outflow, has been questioned by Ulrich and Knapp (1979) hence the "?" in the O.P. column. The other question marks are mainly due to the still uncertain observational situation in the infrared.

A correlation between A_V and O.P. which would be expected for a radiation driven wind but would not necessarily be expected for other driving mechanisms mentioned above is not evident in Table 1. Future observations should clarify this point. Measurement of the total far infrared luminosity of low mass star forming regions, such as those described by Dr. Nordh, is very important to establish L for T Tauri stars and the exciting stars of HH objects.

Interferometric measurements such as those discussed by Drs. Howell and Sibille may tell us whether the stars that excite the winds are single or multiple or whether they are surrounded by massive disks lying close to the stars. Infrared interferometers may also help us to learn more about protoplanets (and hence planets themselves). Since there is more mass and luminosity in the protoplanetary nebulae than in the planets themselves infrared observers have an advantage over astrometric types. A particularly interesting possibility would be to see if preplanetary disks are found in multiple star systems as well as around single stars.

It is hard to think of an area in astronomy that is as rich in promise in the coming decades as is the infrared.

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