STAR FORMATION

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1. Introduction

Star formation is an extremely active area of current research with studies ranging from the detailed properties of forming stars in the Galaxy to the evolution of galaxies at cosmological distances. Some of the problems being tackled are of long standing but many are related to unexpected discoveries which have followed from the application of new and improved observing capabilities throughout the electromagnetic spectrum during the last few years. Amongst others, these include the nature of γ and X-ray sources in molecular clouds, the origin of the molecular mass outflows and various related phenomena (e.g. H_2O masers, hot H_2 emission ...) observed in the vicinity of forming massive stars, the mechanism responsible for generating bursts of star formation in galaxy nuclei and the nature of star formation in cooling flows of intracluster gas. At the present time therefore there would be no shortage of good optical/infrared observing proposals which could take full advantage of the order of magnitude gain in sensitivity and, at least in the infrared, the improved angular resolution promised by most of the proposed VLT projects. The need for improved capabilities in the near and mid-infrared is also being pressed by developments in related observational techniques. In particular, sub-mm and mm wave molecular astronomy is set to advance rapidly during the next few years with the completion of several dedicated large dishes. Far infrared astronomy has also recently come of age with the completion of the IRAS all sky satellite survey and the adoption by ESA of ISO (Infrared Space Observatory) as its next major astronomy mission. As the IRAS data become available, for example, its maps of the galactic plane are already revealing new regions requiring sensitive groundbased follow-up at the highest possible angular resolution while the detection of far infrared emission, probably associated with bursts of star formation, has drawn attention to several thousand previously unremarked galaxies.

Unfortunately, the time scale for realizing the major VLT projects will probably be on the order of ten years. The history of astronomical predictions would therefore suggest caution in preparing too detailed a list of scientific objectives at this stage and would certainly not encourage us to predict the results. It is nevertheless necessary to exercise some scientific judgement in

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attempting to optimize the design and instrumentation of these new facilities. After briefly summarizing some of the current problems and recent observational results therefore I will attempt here to demonstrate that, for star formation studies, the most significant performance gains of VLTs will be achieved for high resolution spectroscopy in the visible/near infrared and for infrared imaging and possibly interferometry in the mid infrared.

2. A Brief Review

While it is clearly neither possible nor necessary here to attempt an extensive review of the subject, I have compiled in table 1 a list of current questions in star formation research which are still likely to provide the basis of future programmes for many years to come. One impression which I hope that this list conveys is that star formation is now being observed throughout the Universe and mostly in situations where even such basic questions as the triggering mechanisms are still largely unanswered. Even within our own galaxy, the relative importance of spiral density wave, SN, HII, T Tauri or even possibly other shock phenomena capable of compressing and initiating the collapse of molecular clouds is not yet well established. The detailed mechanisms operating in more recently studied environments such as star burst nuclei, cooling flows onto cD galaxies and giant elliptical galaxies are less well understood and even the observational conclusions tend to be controversial at the present time. Initial mass functions are, at best, poorly known in most of these situations. IMF's deduced from observed evolved stellar populations or from population syntheses tend to be represented as continuous power law functions with low or high mass cutoffs. Many individual star forming regions within the Galaxy however seem to contain either only relatively low mass (T Tauri) or conversely mainly high mass stars implying a more bi-modal distribution. It will probably be a long time before theoreticians can help in resolving this question by predicting the mass spectrum of fragmenting clouds as a function of the initial conditions! Theoretical progress has been made in collapse models however which are now at a stage where further observational input regarding the basic initial conditions and magnetic fields will become increasingly necessary.

Progress in all of these areas will require a wide range of observational input. As a background to discussing the specific uses of VLT's however I will elaborate on just two of the topics listed in table 1 in more detail - pre-main-sequence evolution and star burst nuclei.

Table 1. Star Formation - Some Current Topics and Questions.

Trigger Mechanisms -	Relative importance of spiral density waves, SN, HII, T Tauri or other shock mechanisms in spiral galaxies? Mechanisms in star burst nuclei and non-spiral galaxies e.g. LMC, ellipticals.
Fragmentation -	IMF dependence on environment? Origin of low and high mass cutoffs? Is there a case for bi-modal star formation? Distribution of angular momentum in fragmenting clouds - rôle of multiple systems?
Collapse -	Initial conditions? Rôle of rotation, magnetic fields, ambipolar diffusion?
Pre-Main-Sequence - Evolution	Geometry, physical conditions and dynamics of shells/discs around forming massive stars? Luminosity versus ionization rate for high mass stars? Nature and mechanisms for mass outflows - ionized, molecular, bi-polar?
Star Burst Nuclei -	Models? Need for interaction rather than repetitive triggering? Relationship between star formation and Seyfert activity?
Galaxy Evolution -	Is star formation producing colour evolution of giant ellipticals at high z? Do cD and possibly other galaxies evolve due to star formation out of cooling flows of intracluster gas?

Pre-main-sequence Evolution. Progress in this area has been made in recent years both using high resolution optical spectroscopy to study low mass stars (mainly T Tauri), which can become visible during their p.m.s. phase, and infrared, mm wave and radio studies of dust embedded, high mass, forming stars and their interaction with their surrounding molecular clouds. These objects do not appear to become visible during their p.m.s. phase and their infrared properties are more or less consistent with early hydrodynamic models (e.g. Larson 1973) which showed that cloud fragments should collapse non-homologously i.e. the stellar core forms within an initially infalling and subsequently (due

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to radiation pressure) expanding cocoon. One disappointment however has been the lack of convincing evidence that any of the objects detected so far are protostellar in the strict sense of being in the collapsing, gravitationally heated phase (see for example the review by Wynn-Williams (1982)). Several cool objects detected recently in the sub-mm region are probably the most likely candidates. The famous BN object in Orion believed to be protostellar for some time after its discovery in the late 1960's, is clearly not and may even be a main sequence B star. Many other objects detected in recent years are believed to be p.m.s. massive stars however mostly because of circumstantial evidence such as their association with OH/H_2O maser emission and their location in plots of luminosity versus ionization rate (n_e^2V) such as the one shown in fig. 1 due to Moorwood and Salinari (1983). These particular objects are the most probable H_2O maser counterparts known and the quantity n_e^2V has been derived from Brγ and Brα hydrogen recombination line spectroscopy in the near infrared. It will be noticed that the ionization rates in most cases are lower than expected for ZAMS stars of the same luminosity (solid curve) and for some objects, presumably the least evolved, only upper limits can be placed at ~1% of the ionization rate expected if they were on the main sequence. Within the luminosity range corresponding to B stars however, it will be noticed that a few objects lie to the right of the ZAMS curve i.e. they exhibit ionization excesses which can range up to factors of 10^2-10^3. This discovery, initially made by Thompson (1982), was unexpected and implies a previously unpredicted evolutionary phase. At present, the most plausible explanation appears to be that due to Simon et al. (1983) who have shown that such excesses can be modelled by assuming a dense ($\gtrsim 10^{10}$ cm^{-3}), stellar wind in which the hydrogen can be ionized from the n=2 level by Balmer continua photons. In the case of O stars therefore, this effect would be extremely difficult to detect by simply looking for hydrogen line excesses because of their much lower Balmer to Lyman continuum ratios. Future research into this phenomenon therefore will probably stress more the need for measuring line profiles both to detect directly the presence of winds and to determine the outflow velocities. In addition to ionized winds, many observational phenomena discovered recently in molecular clouds suggest that molecular mass outflows centred on embedded objects are also very common. The evidence includes broad velocity wings seen on CO and other molecular emission line profiles, high velocity H_2O masers (whose proper motions have now been measured in Orion by means of VLBI), the velocity structure in near infrared spectra of CO observed in absorption against embedded objects and the detection of the near infrared quadrupole emission bands of H_2 which implies the presence of shock heated gas at T ~ 2000 K. The nearest and consequently best studied example so far is in the Orion nebula where the outflow phenomena appear to be

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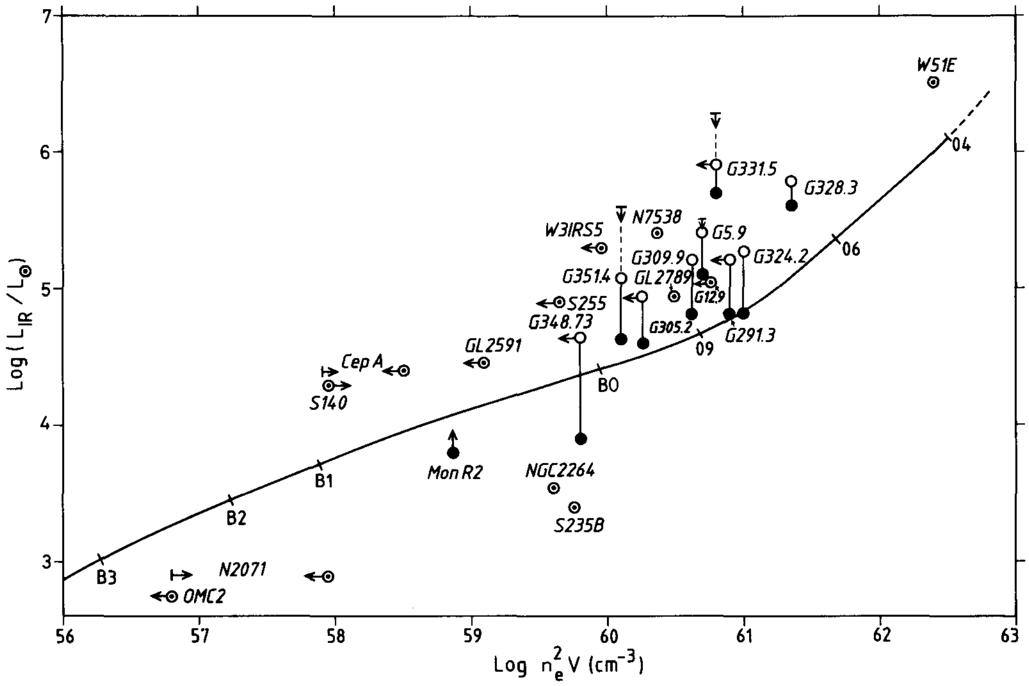

Fig. 1. Luminosity versus $n_e{}^2V$ (α ionization rate, derived from Brγ and Brα hydrogen recombination line observations) for IR objects with associated H_2O maser emission (Moorwood and Salinari 1983). In most cases the ionization rates are much lower than expected for ZAMS stars (solid curve). Some of the objects with luminosities corresponding to B stars however exhibit large ionization rate excesses.

centred on the object IRc2 (Downes et al. 1981), about 10" S of the BN object. IRc2 itself is too faint for near IR CO absorption spectroscopy. Using BN however, Scoville et al. (1983) have identified five separate flow regimes with velocities in the range 15-100 km s^{-1} on the basis of CO spectra such as the example shown in fig. 2. Combining various data, Downes et al. have estimated a mass loss rate of $\sim 10^{-3}$ $M_{\odot}$/yr which, they argue, must have been continuous for $\sim 10^3$ yr so far. The mechanism for such flows is still unknown. Simple radiation pressure arguments are almost excluded however because the momentum in the Orion and other flows exceeds the value of L/c for the embedded object by factors of $\gtrsim$ 100.

IRc2, being more heavily obscured, appears as one of the faintest of a cluster of sources which make up the KL nebula. In fact it was just resolved only recently in the 20μm map made at 2" resolution by Downes et al. (1981). Nevertheless it is argued by Wynn-Williams et al. (1984) that this object probably contributes all of the $\sim 10^5$ $L_{\odot}$ radiated by the KL nebula i.e.

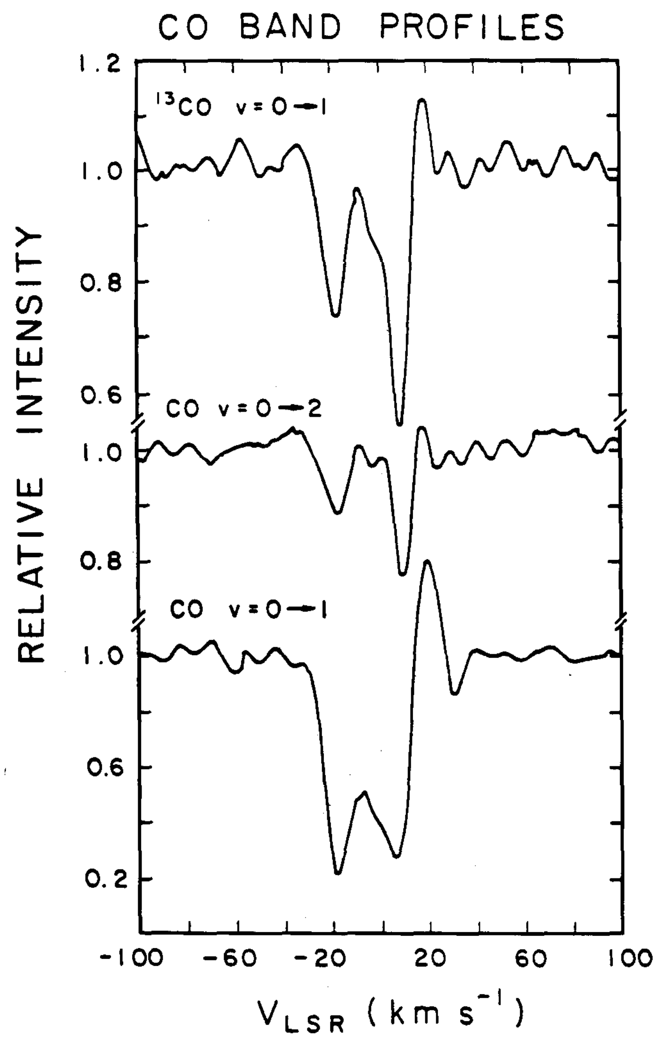

Fig. 2. Composite line profiles for the $^{13}C^{16}O$ 1-0 and $^{12}C^{16}O$ 1-0 and 2-0 bands around 4.6μm and 2.3μm in the direction of the BN object (Scoville et al. 1983).

is ~10^2 more luminous than the BN object and that the other sources in the region can all be explained as density enhancements in the surrounding molecular cloud which are being externally heated by IRc2. As shown by A. Chelli at this meeting, speckle interferometry of IRc2 has now revealed that most of the infrared emission observed probably arises in a disc or ring of material a few × 10^{15} cm in diameter. Using a variety of techniques at close to their present limits therefore a rather detailed picture of the most luminous object in our nearest star forming region and its interaction with its surroundings is just beginning to be built up.

In the case of IRc2, the mass outflow geometry is not very clear but Axon and Taylor (1984) have recently offered evidence, based on TAURUS

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observation of H-H objects, that it might be predominantly bi-polar. This is interesting because the most obvious examples of well collimated bi-polar flows so far seem to be centred on relatively low mass stars, including T Tauri, which are presumed to be obscured by accretion discs. Winds of 100-200 km s^{-1} are observed and both H-H objects and high velocity H_2O masers are observed in the cavities cleared in the surrounding molecular material. Again the mechanism responsible for the flows is unknown. Rather than being an intrinsic property of low mass stars however, it begins to appear more likely that the bi-polarity is simply more evident when the surrounding molecular cloud density is low.

Figure 3 is an attempt to summarize the developments sketched here showing how the partial confirmation of early collapse models has been followed by the unexpected discovery of various mass outflow phenomena which are not so far well understood.

Star Burst Nuclei. The nuclei of many spiral galaxies exhibit enhanced activity over part or all of the X-ray to radio spectral regions which it now appears reasonable to attribute to bursts of star formation. Only a few nuclei however have so far been studied in any detail e.g. M82 and NGC 253 (Rieke et al. 1980), NGC 7714 (Weedman et al. 1981), IC 342 (Becklin et al. 1980), NGC 5253, Circinus and NGC 4945 (Moorwood and Glass 1982, 1984) and the properties of these are far from being homogeneous. While NGC 7714 displays the most intense optical emission lines of any non-Seyfert galaxy for example, the nucleus of M82 is obscured by about 25 mag. of visual extinction. NGC 5253 is unique in being a purely thermal radio source. Circinus and NGC 4945 are the only ones in which nuclear H_2O masers have been detected but both these galaxies have Seyfert nuclei. Several of these galaxies are also isolated while statistical studies tend to indicate that star formation is more common amongst interacting systems. This appears to be the case for example for far IR galaxies detected by IRAS (Soifer et al. 1984). Overall, it is now believed that the luminosities of a few percent of spiral nuclei are probably enhanced by $\sim 10^{10}-10^{11}$ $L_{\odot}$ due to current or recent star formation.

Mid-infrared maps have only been published for M82, NGC 253 and IC 342 (by the above authors) and then only with an angular resolution of a few arcsec. Improved sensitivity and angular resolution ($< 1''$) are now needed if the spatial structure is to be determined over sufficiently small physical scales to test recent theoretical models such as that due to Krügel et al. (1983).

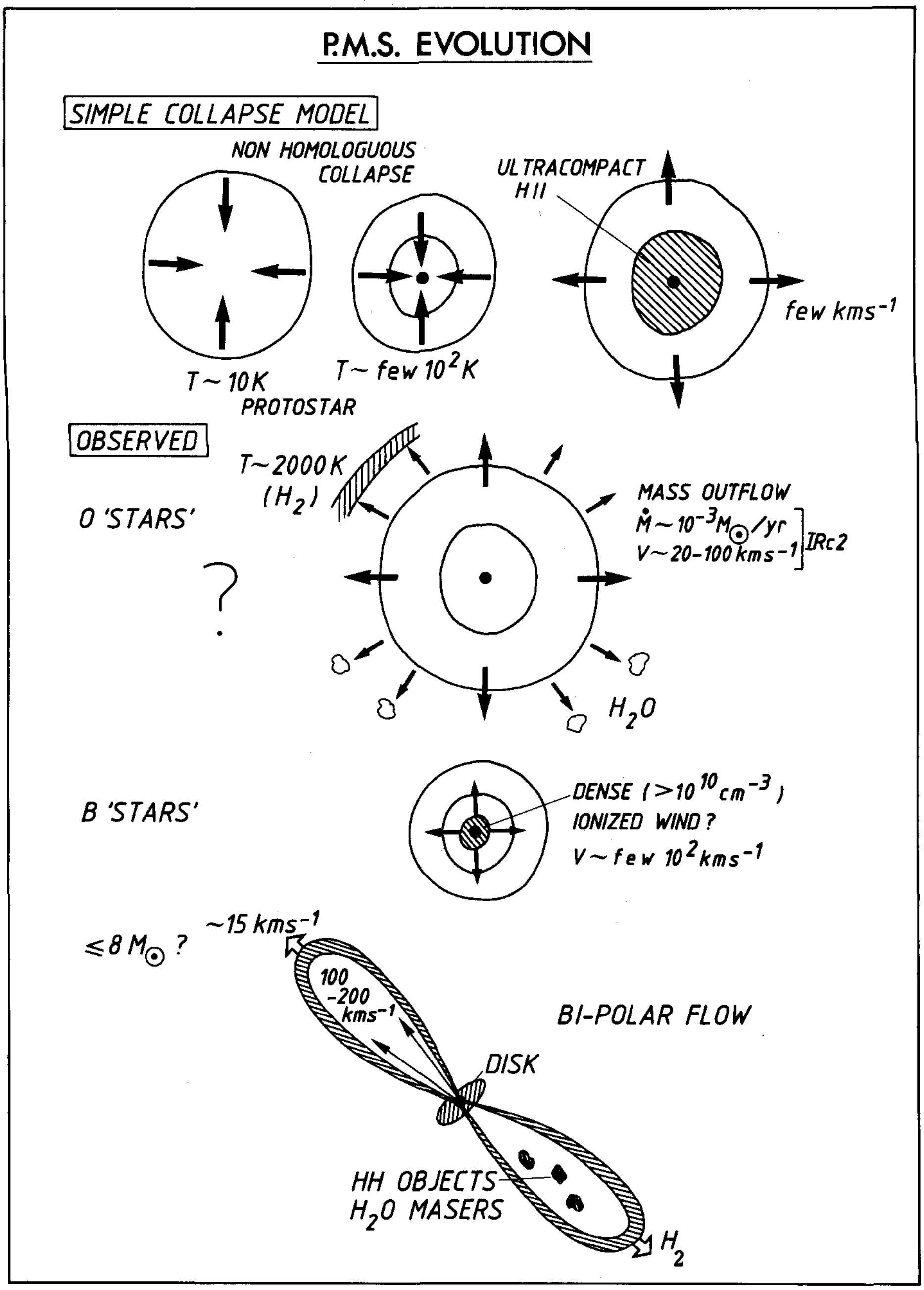

Fig. 3. Hydrodynamic models predict that cloud collapse is non-homologous and that thermonuclear burning can be initiated in the core while the outer part of the cloud is still accreting (cocoon star). At a later stage, radiation pressure results in expansion and eventually dispersion of the cocoon. Observations have revealed the presence of supersonic, ionized winds and molecular outflows which cannot be accounted for within this simple picture and whose origin is presently unclear.

3. Towards Observational Programmes for VLT's

Having alluded to several areas of star formation research which are at or close to present observational limits I will attempt here to demonstrate the main performance advantages to be expected with larger telescopes.

One of these, the larger flux collecting area for photometry and spectroscopy, is relatively obvious providing that careful attention is paid to problems of instrument matching - particularly in the visible (Enard 1983). It is also important to bear in mind the need for minimizing the effective emissivity if the infrared performance is not to be compromised. The main advantage of VLT's for star formation research which I would like to stress above all others however is the possibility for achieving simultaneously both better sensitivity and spatial resolution in the mid-infrared due to the fact that 3-4m class telescopes become diffraction limited at good sites around 10μm. The extent to which this potential gain can be realized depends on the detailed VLT design but, for obvious reasons, I shall keep in mind here the particular possibility of having four telescopes of around 8m diameter distributed over a baseline of ~ 100m.

Infrared Imaging. At present, infrared imaging in the strict sense is very much in its infancy. What has been mostly necessary to date is to laboriously map out regions with a single detector - usually by moving the telescope and hence subject to its pointing/tracking accuracy. In practice therefore, even the theoretical diffraction limits have not often been reached and 20μm maps at 2" resolution such as the ones of the Orion star forming region referred to earlier are rather rare. As demonstrated by McCreight at this meeting however, the situation is now being revolutionized by the development, although unfortunately not yet general availability, of panoramic detectors throughout the groundbased infrared region. In addition to the fact that even modest 32 × 32 pixel arrays bring a factor of $\sim 10^3$ in speed, these devices now allow guided imaging down to the seeing/diffraction limit. As seeing improves with increasing wavelength (~ factor of two better at 10μm than in the visible) and as λ/D = 0.3" at 10μm for an 8m telescope, it should be possible to image with 0.5-1" resolution in the 10μm-20μm region. It is also important to note that, because the background noise $\propto D\theta$, the full D^2 advantage in s/n ratio is achieved when operating at the diffraction limit even when background noise limited. In summary therefore, compared with the currently achieved performance of 4m class telescopes, even a single 8m telescope equipped with a 32 × 32 pixel array should be $\gtrsim 10^4$ faster and provide a factor of 2 gain in spatial resolution. Although the latter might be considered modest, it is as well to remember that the object IRc2, which appears to dominate the Orion region, is only distinguishable from a neighbouring source on the recent 2" maps and not on earlier ones at 5" resolution.

It should perhaps also not be forgotten that the kinds of optical/IR VLT's discussed at this meeting might still be the best sub-mm (~ 350μm) facilities available in the 1990's and that mapping at these wavelengths still promises to be the most effective technique for finding truly protostellar objects.

Infrared imaging/mapping of galactic star formation regions and the nuclei of star burst galaxies therefore should be an important goal for VLT's and, in table 2, I have listed some of the astronomical topics where such observations should be particularly relevant.

Interferometry. At wavelengths shorter than about 5μm, where VLT's can be expected to be seeing limited, the technique of speckle interferometry will still provide for imaging down to the diffraction limit i.e. again a factor of 2 improvement in spatial resolution. This technique is now becoming quite routine and, in addition to the work already mentioned on IRc2, has been used to determine the size of the dust emission region around BN (Foy et al. 1979) and to resolve a number of close multiple systems including the discovery of a cool companion to T Tauri (Dyck et al. 1982). This technique will also benefit from 2D array developments.

The VLT concept considered here also allows, in principle, for multiple telescope interferometry over a baseline of ~ 100m. Although less routine, promising results for IR interferometry at CERGA have been reported at this meeting and the possibility for obtaining spatial resolution down to a few m arcsec would be very exciting for star formation research. This is demonstrated in fig. 4 which is basically a plot of diameter versus temperature for spherical blackbodies with luminosities in the range $1\text{-}10^5$ $L_\odot$. Wavelengths of peak emission, corresponding to the temperature scale, are indicated along the top and the equivalent angular resolution in arcsec for a distance of 500 pc on the right hand ordinate of the figure. The nominal resolution, λ/D, of current 4m telescopes (speckle or imaging) and a 100m baseline interferometer are also shown. In practice, the achievable resolution is slightly better than λ/D as shown by the measured size/colour temperature point for the BN object, close to the 10^3 $L_\odot$ line. Relatively, however, a 100m interferometer is capable of a factor 25 improvement in angular resolution, a larger gain than its maximum sensitivity advantage.

For IRc2, in addition to the size/colour temperature derived for the

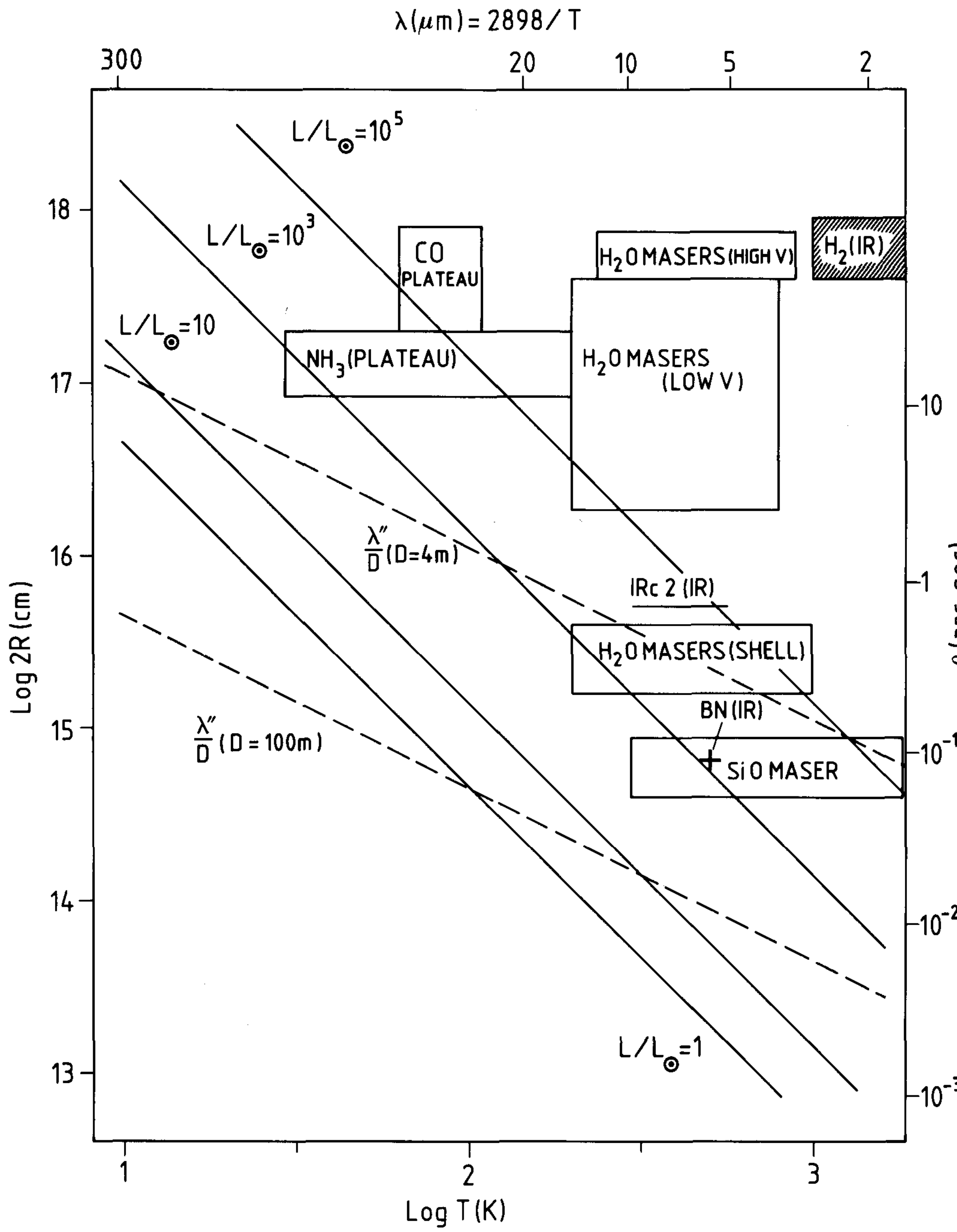

Fig 4. Diameter versus temperature for spherical blackbodies with luminosities in the range 1-10^5 $L_\odot$. The right hand ordinate gives the subtended angle for a distance of 500 pc. The top scale shows the wavelength of peak emission corresponding to the lower temperature scale. The dashed lines indicate the nominal angular resolution achievable with a 4m telescope and with an interferometer having a 100m baseline. Observed IR sizes and temperatures are plotted for BN ($\simeq 10^3$ $L_\odot$) and IRc2 ($\simeq 10^5$ $L_\odot$). For IRc2, the temperatures and distances of various molecular phenomena are also shown.

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annular structure observed with speckle techniques, I have also included on fig. 4 the temperatures and distances from IRc2 of various molecular phenomena as given by Downes et al. (1981). Of particular interest is the fact that those H_2O masers whose spectra exhibit shell type structure do in fact lie close to the infrared emitting annulus in this diagram and that even smaller scale structure is implied by the presence of the SiO maser. Even for the most luminous forming star in Orion therefore it can be expected that higher spatial resolution interferometry at a range of infrared wavelengths will reveal additional density and/or temperature structure. Long baseline interferometry would obviously be of interest both for extending such detailed studies to a much larger sample of luminous sources and for obtaining information on dust shell/disc sizes for nearby objects down to luminosities of a few $L_{\odot}$. The diagram also shows that nearby, luminous, objects could still be resolved even if they have temperatures of several thousand degrees.

The application of interferometric studies to extragalactic work is more speculative at the moment because of the additional sensitivity requirements but it would clearly be of interest to obtain structure information within the cores of the few brightest star burst nuclei.

Spectroscopy. With a factor ~ 16 increase in collecting power it is clear that VLT's could extend and probably revolutionize spectroscopic studies of star forming regions. In the visible, it would allow line profile studies of the outer atmospheres of T Tauri and other medium to low mass pre-main-sequence objects which are presently at or beyond the limits set by the photon collection rate of available telescopes. Their performance for infrared spectroscopy has been discussed in some detail elsewhere (Moorwood 1983) where, amongst other aspects, attention was drawn to the fact that the sensitivities achievable with VLT's for high resolution near-mid infrared spectroscopy within the atmospheric windows will far exceed those of the space missions already mentioned. At the same time they will also provide much better seeing/diffraction limited spatial resolution than these much smaller (< 1m) cooled telescopes. On the basis of the recent work already reviewed, the great potential of infrared spectroscopy for star formation studies is that it provides the possibility for studying both ionized and moelcular gas in the highly obscuring clouds in which massive stars appear to form. Infrared hydrogen recombination lines for example have already been demonstrated in many cases to be a more sensitive probe for dense ionized regions than observations in the radio continuum where they are optically thick. Further studies of the ionized wind phenomenon certainly require improved infrared spectroscopic capabilities in order to determine both line ratios and profiles. Infrared spectroscopy also provides the only direct means for

Table 2. Star Formation - Some VLT Observational Programmes.

Infrared Imaging

- 2-20μm images at 0.5-1" resolution of fields < 1'
  350μm maps at ≃ 10" resolution?

Star formation regions in the Galaxy.

- selected from HII, CO, OH/H_2O maser, far IR (IRAS, ISO) etc surveys
- astronomical interest for cluster scales, inventory of forming stars in molecular clouds, association of phenomena (e.g. IR objects with masers, SN or other shock fronts), discovery of new forming stars and possibly protostars for follow-up observations.

Star burst nuclei.

- selected optically or from far IR surveys (IRAS, ISO)
- astronomical interest for determining spatial structure of star forming regions for comparison with radio maps and model predictions (e.g. ring structures).

Infrared Interferometry

- 1-20μm, 350μm, angular resolution from few 10^{-3} - 1 arcsec.

Star formation regions in the Galaxy.

- shell/disc geometry, protoplanetary discs?
- shell/disc temperature structure (multi-colour interferometry)
- close multiple systems

Nearby galaxies.

- Compact cores (0.1" = 2pc at 4 Mpc)

High Resolution Spectroscopy (R ~ 10^4-10^5)

visible - velocity structure in outer atmospheres of T Tauri and other medium to low mass p.m.s. objects.

2-5μm - dense ionized regions and winds (H recombination)

high temperature shocks (H_2)

line of sight molecular mass motions (CO absorption against embedded objects)

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detecting H_2 in star forming regions and high resolution studies of the quadrupole emission bands will provide more information on the physical conditions and velocities in the high temperature shocked regions near to embedded objects in molecular clouds. It will also be possible to extend to much fainter embedded objects the technique of 2.3μm and 4.6μm CO absorption spectroscopy discussed earlier with which both the line of sight speeds and direction of molecular mass motions can be determined. There are thus already rather specific interests, based on current work, on the possibility for spectroscopy with a resolution of a few km s^{-1} ($R \sim 10^4$-10^5) in the 2μm-5μm region. Because this spectral range contains a number of other molecular bands however it is likely that other applications will become apparent once high quality spectra become available for the brighter known sources.

Emission line spectroscopy of star burst nuclei in the hydrogen recombination lines and H_2 will also be of interest. Such measurements are currently at the limit of 4m class telescopes but measurements are available now for a few galaxies and, in extreme cases like M82 whose nucleus is heavily obscured in the visible, infrared spectra provide the only means for estimating the quantity of ionized gas present.

4. Conclusions

For star formation studies, the main interest in VLT's will centre on their infrared performance advantages and in particular the possibility of achieving a factor of 2 gain in spatial resolution simultaneously with a factor of more than 10 in sensitivity for direct imaging of star formation regions in our own and nearby galaxies. It is thus important to pay attention to minimizing the telescope emissivity during the detailed design phase in order to maximize sensitivity in the thermal infrared (~ 2-20 μm). An additional interferometric capability over a baseline of ~ 100m would open up completely new possibilities for studying the geometry and temperature structure of dust shells/discs around forming stars. The collecting area advantage of VLT's will permit the exploitation of several high resolution spectroscopic techniques in the visible and near infrared which are currently at the limit of available telescopes.

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DISCUSSION

G. Burbidge: Is it the case that you now feel that there is very little evidence for collapsing objects in star forming regions? If this is the case it is not surprising since the gravitational collapse time scale in star formation is much shorter ($\sim 10^{-2}$) than the timescale for thermonuclear evolution. Thus for the same mass range only a very small fraction of the objects seen should be collapsing. The majority should be evolving off the main sequence rejecting matter.

A. Moorwood: Yes, I don't believe there is evidence that any of the embedded objects discovered in molecular clouds are in the gravitational collapse phase whereas there is clearly mass outflow in many cases. Ionised gas has also been found to be associated with several objects originally thought to be protostellar.

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I. Appenzeller: I fully agree that so far we have no really hard evidence for observationally identified forming stars which are still in the collapse stage. However, it is very difficult to determine whether an IR source is still in this stage or not. In the case of the BN object it has, e.g., been argued that the redshifted components of the CO IR absorption line profiles (presented by Dr. Moorwood) are in fact caused by a still infalling outer shell of this object. Furthermore, as the collapse time cannot be shorter than the free-fall time, the time between the last fragmentation and the beginning of hydrogen burning is comparable to the nuclear life time of an O star. Hence, collapsing clouds should be observable.

A. Moorwood: It is true that Scoville et al. (1983) concluded that one of the CO features in their spectrum of BN implies the presence of infalling gas. What is puzzling is that this gas is apparently rather hot (~600K) and circumstellar whereas BN itself exhibits a dense, ionized, supersonic ($V > 100$ km s^{-1}) wind.

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