mately to be limited by residual optical (mostly zonal) aberrations, even at this very low level. It will be interesting to see whether the CAT optics, made by the same manufacturer under even tighter specifications, will produce still better images under optimum conditions.

Being far from ungrateful, however, we wish to conclude by paying tribute once again to those responsible for this achievement: to the firm of Grubb Parsons for their outstanding optical and mechanical craftsmanship, to the ESO Optics Group for their invaluable help in testing and aligning the optics, and to the ESO Controls Group and the workshops of Copenhagen University Observatory for the successful combination of control system and autoguider.

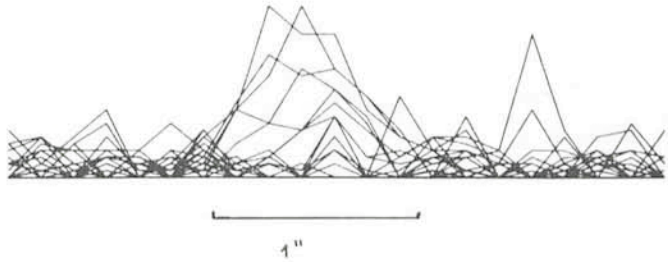

Fig. 2: *A scan through one of the images in figure 1, made with the PDS microdensitometer at the Lund Observatory through a 10 × 10 micron square aperture.*

The Problem of Star Formation—and what Ten Nights of Sub-millimetre Observations with the VLT Could Contribute to its Solution

P. G. Mezger

Astronomical observations are regularly carried out over the whole electromagnetic spectrum, from γ-rays to low-frequency radio waves. There are few unexplored "holes", but one of these—in the neighbourhood of 1 mm—is exactly where we expect most of the radiation from stars during their early stages of formation. The VLT would be ideally suited for ground-based observations in the sub-millimetre range, because of its large surface and good angular resolution. Dr. Peter Mezger of the Max Planck Institute for Radioastronomy in Bonn explains how the VLT can make a very important contribution to the study of stellar formation.

Sub-millimetre Observations, Star Formation and the VLT

The transformation of gas into condensed objects, either ordinary main-sequence stars with masses ~0.1–100 $M_\odot$ or perhaps also much heavier supermassive stars, is one of the most fundamental processes in the Universe. Star formation plays a leading role in the formation of galaxies, in the chemical evolution of the interstellar matter (i.e. its enrichment with elements heavier than ^{4}He) and may well be related to some of the phenomena associated with radio galaxies and quasars.

In spite of a wealth of radio and IR observations related to both dense molecular clouds (out of which protostars form) and pre-main-sequence evolutionary stages of massive stars, the basic process of the formation of protostars out of the interstellar matter is far from being understood, even in a qualitative way. The reason is that the formation of protostars occurs at very low temperatures of the interstellar gas (typically ~10 K) and that the outer shell of the contracting protostar remains at such low temperatures until nuclear burning starts at its centre. Thus the Planck curve for 10 K (shown as dash-dotted curve in Figure 1) is an upper limit for the intensity of both continuum and line TE radiation emitted by dense molecular clouds and protostars in their early evolutionary stages. This curve peaks at ~500 μm (= 0.5 mm). In Figure 1 is also shown the transparency (heavy curve) of the atmosphere for an amount of 1.3 mm of precipitable water, conditions as they prevail at an altitude of ~3,000 m for about 30 % of the clear nights. One recognizes a number of atmospheric windows whose transparency decreases with decreasing wavelength. Below ~300 μm the atmosphere is practically opaque. The wavelength range between 1.8 mm and 300 μm, although accessible for ground-based observations with a telescope placed at a very high and dry site, is largely unexplored. This is due to both a lack of sensitive radiometers and of radio telescopes with a sufficient surface accuracy of its reflector.

Promising developments of both coherent radiometers (for spectroscopy) and incoherent radiometers (bolometers for broadband continuum observations) for the sub-millimetre wavelength range are in progress in various laboratories in Europe and the US. But even the second generation of mm-telescopes, now being planned or under construction, are only marginally usable for sub-millimetre observations. The reason is that the quality of a telescope for coherent detection is determined by the rms deviation of its reflector surface from a best-fit paraboloid, and this in turn is determined by the surface accuracy of the reflector panels, the accuracy with which these panels can be adjusted, and by the design of the reflector back-up structure. Most mm-telescopes in operation today have rms deviations $\sigma \gtrsim 100$ μm. For the new large mm-telescopes one anticipates rms deviations in the range $90 \gtrsim \sigma/\mu m \gtrsim 50$, which degrade the telescope characteristics (such as gain, aperture, and beam efficiency) according to exp

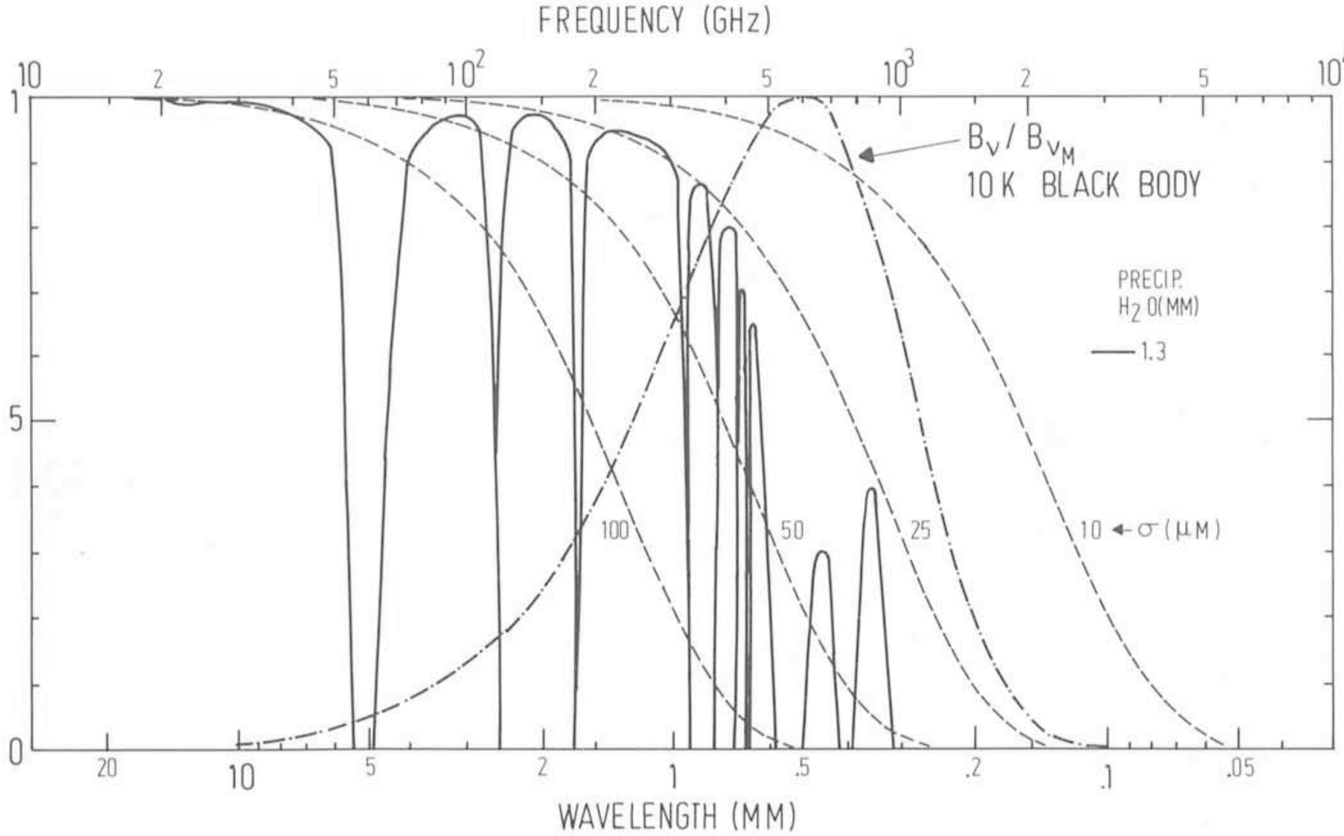

Fig. 1: *Transparency of the atmosphere (heavy curve) for an amount of 1.3 mm of precipitable water. Relative change of gain and efficiency of a telescope used for coherent detection (dashed curves). Curve parameter is the rms reflector deviation σ from a best-fit paraboloid. And (dash-dotted curve) normalized Planck radiation curve for 10 K. (Adapted from Leighton, 1978, Final Technical Report NSF Grant AST 73–04908).*

$\{-(4\pi\ \sigma/\lambda)^2\}$. This function is shown in Figure 1 for different values of σ as dashed curves. Telescopes to be used in the sub-millimetre range $\lambda \gtrsim 300$ μm should have rms deviations $\sigma \lesssim 10 \sim 20$ μm. Today, such accuracies are only attained by optical reflectors and this explains why at present observations in the sub-millimetre range are exclusively done with large optical telescopes, mostly at twilight and during moonlight nights. Considering these facts und the observing interests of me and some of my associates at the MPIfR it is obvious that we would use VLT observing time for an investigation of the early phases of protostars. Within ten "nights" at the VLT, sub-millimetre observers with improved coherent and incoherent radiometers should be able to gain insight into some of the basic processes of star formation. I have deliberately put "nights" in quotation marks, since sub-millimetre observers would probably always request only such observing time on a VLT which could not—or only marginally—be used by optical observers.

What Do We Know about Star Formation?

From recent radio and infrared observations we have learned quite a lot about the pre-main-sequence evolution of massive OB stars. We know that these stars form out of dense clouds of interstellar gas where practically all hydrogen is in molecular form. H_2 has no observable radio transitions, but since it is the most abundant collision partner its density can be crudely estimated from the intensities of collisionally excited transitions of molecules such as CO, CS, CN or HCN. From such observations we know that giant molecular clouds have masses 10^5–10^6 $M_\odot$, mean densities of 10^3–10^4 cm^{-3} and kinetic gas temperatures $\gtrsim 10$ K. And it appears that at densities $\gtrsim 10^4$ cm^{-3} gas and dust are in thermodynamical equilibrium. But what initiates (or inhibits) star formation in these clouds we do not know. We have learned from recent model calculations that (at least the more massive) stars form by accretion. At the centre of a contracting protostar, density and temperature become high enough for hydrogen burning. An embryo star forms, which grows by infall from the outer layers of the protostar und therefore evolves up the main sequence. After the embryo star stops accreting, a shell of gas and dust is left behind, which is visible first as a FIR source and subsequently as a compact H II region. The sequence of observable stages of the protostellar shell, after hydrogen burning has started at the centre of the embryo star, is shown in Figure 2. But practically nothing is known about the earliest evolutionary stages of protostars, when these objects should appear as dense but isothermal condensations in cool molecular clouds.

The situation becomes even worse if we turn to the formation of lower-mass stars (i.e. stars with masses less than a few solar masses) which account for the bulk of the mass of stars. While both high-mass stars and lower-mass stars form out of massive and dense clouds of interstellar matter, the former appear to form predominantly in the main spiral arms, the latter appear to form predominantly in the interarm region (observable in some cases as T-Tauri associations). What determines the stellar birthrate function, why is it easier for nature to form low-mass stars than massive stars (in contradiction to what the Jeans criterium tries to tell us), and which fraction of mass ends up in substellar objects with masses $\lesssim 0.07\ M_\odot$? Answers to these questions will probably only come from sub-millimetre and FIR observations.

Emission from Dust, from Molecules and from Atoms at Sub-millimetre Wavelengths

Let us first consider the quasi-thermal emission from cool dust. At sub-millimetre wavelengths $\gtrsim 300\ \mu m$ even for the giant molecular clouds the average dust optical depth is small, so that protostars which form deep in these clouds, due to their higher densities and hence optical depths, should be observable as emission centres or "hot spots". Hildeband and his colleagues of the University of Chicago, using optical telescopes at Cerro Tololo and Mauna Kea, have actually observed thermal dust emission from cool molecular clouds and from the globule Barnard 335. For the latter the colour temperature of the dust was found to be ~ 8 K. This type of observations with telescopes of high angular resolution (a 25 m VLT at λ 500 μm will have a HPBW of ~5 arc sec) should be a very powerful tool for the investigation of the earliest protostellar stages. At present, one uses composite Ge-bolometers which are

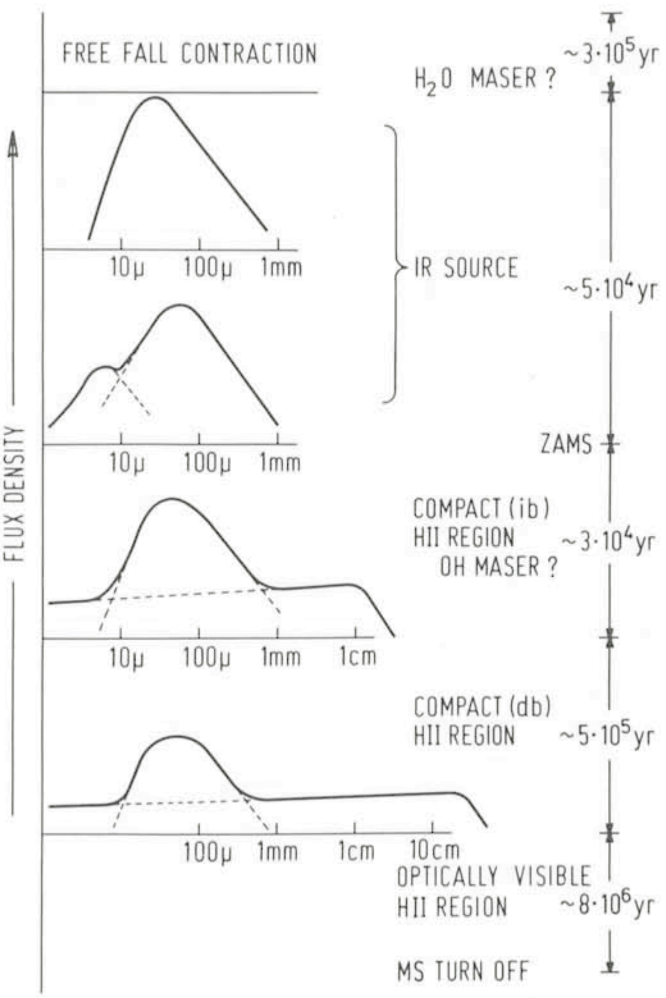

Fig. 2: *Observable spectra of an evolving massive protostar. Time scales on the right side correspond to a main-sequence star of 17 $M_\odot$. During the free-fall contraction the protostar should be observable as a 10 K black body (see Fig. 1). A compact radio H II region forms after the accretion has stopped and the star has attained the ZAMS. The maser, IR and Radio stage of an O star together last for ~ 5–10 % of its MS life time (Mezger, 1978, Infrared Astronomy [G. Setti and G. G. Fazio, eds.] D. Reidel Publ. Co. p. 1.).*

cooled to temperatures of ~ 1.5 K, attainable with pumped liquid ^{4}He. However, temperatures as low as ~ 0.3 K can be attained by using ^{3}He as a coolant, and this should increase the sensitivity of future bolometers by at least an order of magnitude.

The optical depth of dust is independent of temperature and varies only slowly with frequency. The spectral shape of optically thin dust radiation thus is still very similar to that of a Planck curve. On the other hand the optical depth of the rotational transition of a molecule increases with T_{ex}^{-2}, but decreases rapidly with increasing rotational quantum number J or decreasing wavelength once E(J) > kT. Figure 3 shows the intensity distribution of rotational lines of the CO molecule, computed for $T_{ex} = 10$ K; curve parameter is τ_{co} (J = 1→0), the optical depth of the lowest transition. Even for τ_{co} (1→0) = 10–100 (which may be typical for dense molecular clouds) the lines with J $\gtrsim$ 4-5 become optically thin and thus allow observations of condensations in the cloud. Again, the high angular resolution of the VLT should allow to observe dense condensations inside the optically thin clouds, which I would expect to be the first evolutionary stages of protostars. Equally important is the fact that the analysis of several (optically thin) rotational transitions of one molecule leads to a much more accurate determination of the physical state of a molecular cloud than does the currently applied method of observing one handy transition at mm wavelengths $\lambda \gtrsim 2$ mm of different molecules with different dipole moments. Plambeck and Williams, for example, compared density determinations from the J = 1→0 and 2→1 transition of the isotopic ^{13}CO, with corresponding densities derived from one transition of CS, CN and CHN, respectively. They found that the latter method overestimates densities by typically a factor of 10! This is one reason why the sub-millimetre range with its possibility to observe several rotational transitions of one molecule, is so important for the astrophysical application of molecular spectroscopy. Other reasons are that several molecules, such as the possibly very important species of hydrides, have such low moments of inertia that their rotational spectra only start at wavelengths < 1 mm. Observations of

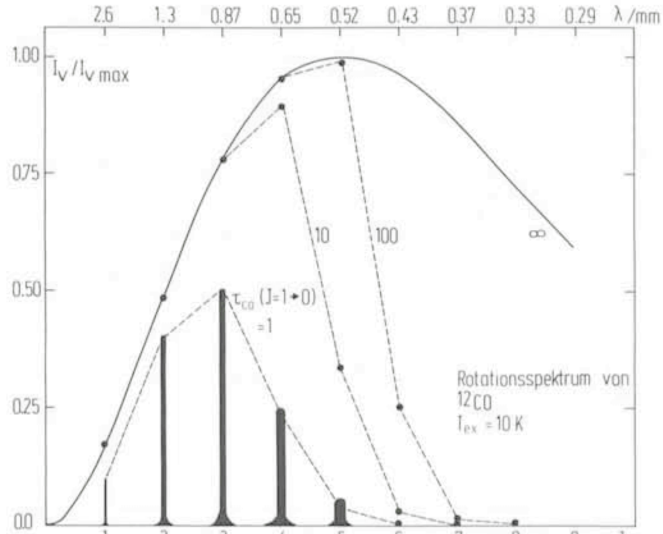

Fig. 3: *Intensities of rotational lines J→ (J-1) of the ^{12}CO molecule computed by Schmid-Burgk for a plane-parallel gas layer in TE at 10 K. Curve parameter τ_{co} (J = 1→0) is the optical depth for the lowest rotational transition. The curve $\tau_{co} \rightarrow \infty$ corresponds to the Planck curve. Note that the width of rotational lines increases approximately proportional with J.*

hydrides may in fact play a key role for our understanding of interstellar chemistry. Of special interest for astrophysics are transitions of atoms and atomic ions since they allow abundance determinations. Furthermore, fine structure lines of atoms and ions as C° and C^{+} provide part of the cooling for interstellar clouds. The λ 610 μm line of C° should be of special interest for the physics of dense interstellar clouds and may be observable with a ground-based telescope. However, only heterodyne radiometers will provide sufficient sensitivity for sub-millimetre spectroscopy. As mentioned before, intensive development work on this type of radiometer is in progress in several laboratories in Europe and USA:

There are other, more speculative, objects to be observed in the sub-millimetre range, such as the redshifted dust radiation from giant elliptical galaxies in their formation stage. The cosmological implications of such observations are obvious. We may also envisage a galactic survey for both the quasithermal emission from cool dust and for some higher rotational (and therefore optically thin) transitions of the CO molecule. (But of course such a survey would be carried out not with the VLT but with small telescopes.) This should lead to a much more realistic picture of the distribution of interstellar gas than the present one which is based on the observation of the opaque $J = 1 \rightarrow 0$ transition of ^{12}CO.

European Astronomers Discuss the Use of the Space Telescope (continued)

With the publication of the Proceedings of the ESA/ESO Workshop on "Astronomical Uses of the Space Telescope", held in Geneva on February 12–14, 1979, it is now possible to better judge the interest of the European astronomical community in the Space Telescope. The Proceedings of course only represent the "official" part of the meeting. There were also lively discussions among the 186 participants and it is impossible to write them all down!

The Space Telescope

The workshop was opened by three speakers—Longair, O'Dell and Macchetto—presenting a general introduction of the technical as well as the political aspects of the ST.

In his contribution "The Space Telescope and its capabilites", Longair compared ST with ground-based telescopes, stressing the improvements in angular resolu-

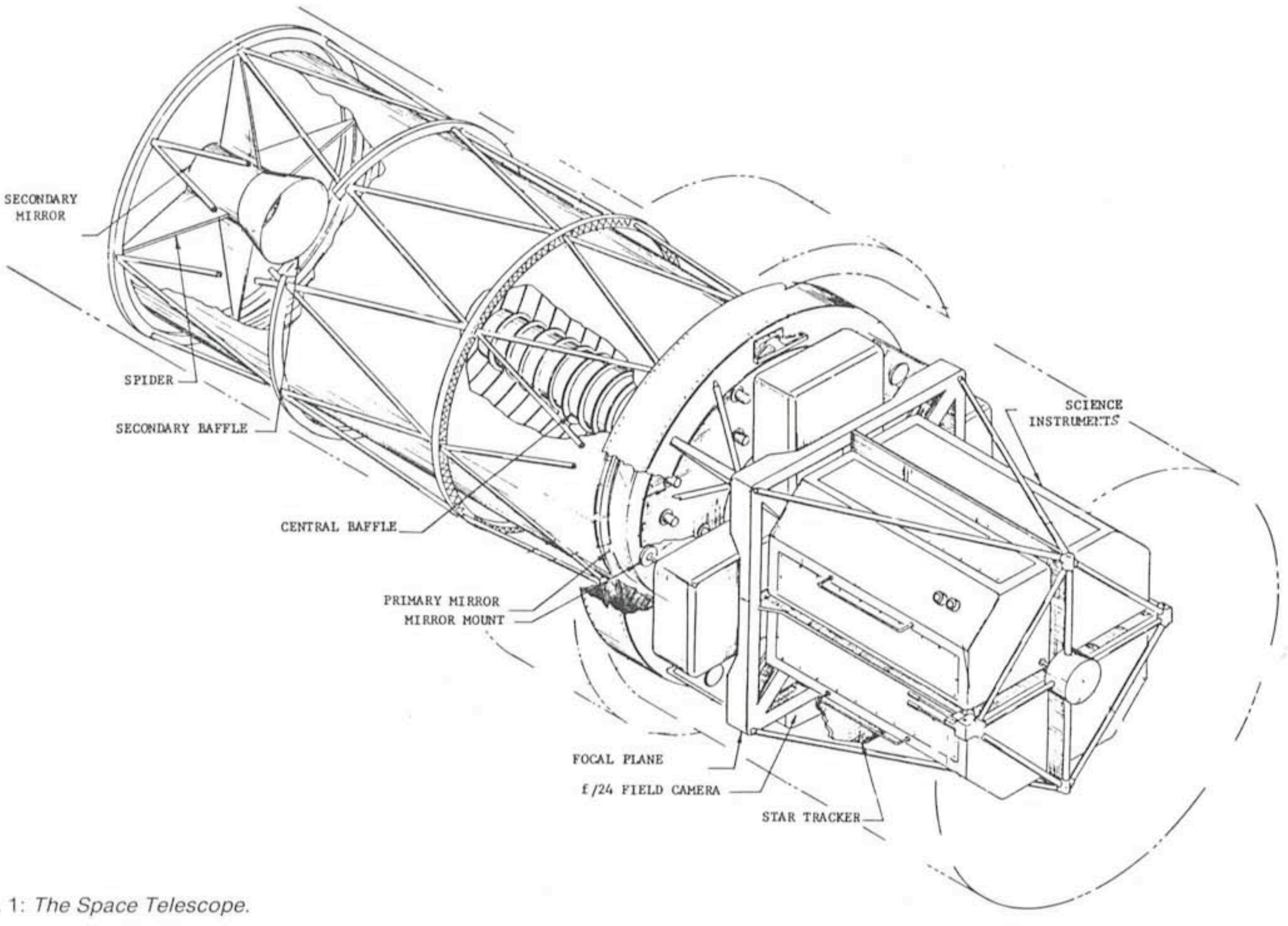

Fig. 1: *The Space Telescope.*