N87-24375

SUMMARY OF SYMPOSIUM: LOW LUMINOSITY SOURCES

FRANK H. SHU
Astronomy Department, University of California, Berkeley, CA 94720

INTRODUCTION

Together with Eric Becklin I have the unenviable job of trying to summarize a very diverse and productive conference. To break the job down to more manageable proportions, we have decided that I would cover the low-luminosity sources, and Eric the high-luminosity sources. Rather than try to encapsulate the many papers presented on the former subject, I shall begin my review with a summary of some major themes and end with a few speculations on possible theoretical mechanisms.

ORIGIN OF INFRARED EXCESSES OF *IRAS* GALAXIES

One of the most basic issues addressed at this meeting is surely the question of the origin of the infrared excesses of *IRAS* galaxies with large ratios of infrared to optical luminosities. Three leading contenders were put forward as the fundamental energy source powering the phenomenon:

(a) the physical collision of two nuclear disks,

(b) a burst of star formation in the central kpc of a galaxy,

(c) reprocessing of the light from an active galactic nucleus (AGN).

In particular, Martin Harwit started his presentation of the model developed by himself and his colleagues with some strong philosophical arguments why candidate *(a)* should be favored over candidate *(b)*. Now, I personally am very susceptible to such an appeal, and am persuaded that the only viable counter to a good philosophical point is another good one. Let me therefore give what is probably the standard party line on this point, namely, the consideration of energy efficiencies.

(a) If one has a gram of matter and one wishes to generate light, dropping this matter down a galactic potential well characterized by a velocity of 300 or 500 km/s (*i.e.*, roughly 10^{-3} the speed of light) will yield a kinetic energy (which can be coverted to heat and photons in inelastic collisions) of $\sim 10^{-6}\ mc^2$.

(b) Dropping the same gram of matter onto the surface of a main-sequence star will liberate about the same potential energy as dropping it through a large galaxy, but if this (hydrogen-rich) matter later undergoes fusion reactions, the efficiency increases to about 1%. Of course, in high-mass stars, only about 10% of the entire mass is ever burned, so the overall energy release is more like $\sim 10^{-3}\ mc^2$.

(c) One can do better by dropping the same gram down a black hole. The efficiencies are not known accurately, but most estimates for swirling accretion in a disk geometry yield an energy release of about $10^{-1}\ mc^2$.

The argument now proceeds that if one wishes to explain the most energetic members of any class of phenomenon, it pays to be as efficient as possible in the use of matter to create energy. From this point of view, when considering the most luminous of the *IRAS* galaxies, it is natural that one should first examine the AGN possibility represented by the last member of the above list. For lower and lower luminosity sources, one can perhaps safely proceed further and further back on the list. But the penalty for using one of the earlier mechanisms to explain a very high luminosity source is that the fundamental energy supply cannot last very long, and therefore the likelihood of seeing the phenomenon at any given time becomes small.

Nevertheless, I believe that ample evidence was presented at this meeting that starbursts are behind many of the less energetic examples of strong infrared-emitting galaxies. The most compelling argument concerned the spatial location and extent of the infrared emission and the associated molecular gas. Sofue, Lo, and Turner showed us beautiful maps that indicated large amounts of molecular gas, the raw material for star formation, are found in the central few hundred parsecs of candidate starburst galaxies. The total amounts of gas in these galaxies deduced from CO observations, as reported by Dave Sanders and others, is often disturbingly large – in excess of 10^{10} $M_\odot$ in some cases. The associated far infrared emission, as detected from multi-aperture studies, is frequently spatially extended, ranging in scale from 10^{-1} kpc to 10^{1} kpc. And, as we learned from Frank Low's discussion, the *IRAS* observations themselves used in a super-resolution mode can sometimes rule out pointlike (*i.e.*, AGN) models for the source of the warm dust emission.

Equally conclusive for me were the many correlations with indicators of star formation: hydrogen recombination lines, especially the Brackett lines recommended by Paul Ho – shocked molecular hydrogen, as reported upon by Dr. Joseph and others – various spectroscopic diagnostics of young massive stars, especially the CO bandheads associated with M supergiants discussed by George Rieke – etc. The correlation with radio continuum emission was also good – in fact, inexplicably good – and I thought I heard a collective sigh of relief from the audience when Dr. Eales reported that the correlation of nonthermal radio continuum with far infrared emission may, after all, have more scatter than originally thought.

DEFINITION OF A STARBURST

Another topic which occupied much of the attention of this conference's participants seemed to be the question of the proper definition of a starburst galaxy. Dan Weedman offered a particularly sweet definition in his talk, but I gathered that most people favored a definition that would take into account some notion of a high star formation efficiency. An operationally useful measure of the rate of star formation per unit mass of raw material is the ratio

$$L_{IR}^{OB\ sf}/M_g, \tag{1}$$

where $L_{IR}^{OB\ sf}$ is the part of the (far) infrared luminosity of a galaxy which can reasonably be attributed to OB star formation and M_g is the total mass of (molecular) gas in the galaxy. Many of the papers of the conference addressed the issues of how to derive either the numerator or the denominator of the above ratio.

The best determinations of $L_{IR}^{OB\ sf}$ involved physically motivated decompositions of the infrared emission seen in the four *IRAS* bands. The models discussed by Peter Mezger, Jean-Loup Puget, and reviewed by George Helou on behalf of Michael Rowan-Robinson and Tieje de Jong, had various combinations of the following four elements in their decompositions:

$$L_\nu = L_\nu^c + L_\nu^w + L_\nu^h + L_\nu^{AGN}, \tag{2}$$

where L_ν^c is a cold or "disk" contribution which comes from H I and cold H_2 gas, L_ν^w is a warm or OB stars contribution which can be associated with a "starburst" in the extreme cases, L_ν^h is a hot or small-grain component associated with non-equilibrium heating of PAH particles, and L_ν^{AGN} is a Seyfert component associated with dust heating by a central engine. The consideration of PAHs is mostly important at 12 μm; strong emission at 25 μm may need to invoke an AGN component, but as Carol Persson has argued, the main contributors at 60 and 100 μm, where the bulk of the radiant energy is generally emitted, are the "warm" and "cold" components in most galaxies. Although the details differed somewhat, I gathered the impression that most of the workers in this field got results in reasonably good agreement with one another. For example, as a rule of thumb, roughly half each of the far infrared emission from a "normal" spiral galaxy comes from the warm and cold components. In principle, then, we now have the numerator $L_{IR}^{OB\ sf}$ as the integral of L_ν^w over frequency ν.

The determination of the denominator M_g in equation (1) turned out to be more controversial. Dr. Krugel is correct, in principle, when he says that the best method for estimating the total gas mass is from measurements of the submillimeter and millimeter luminosities. At submillimeter and millimeter wavelengths, the thermal emission from dust grains can be assumed to be optically thin, and the Planck function can be approximated accurately by its Rayleigh-Jeans limit, so that the total thermal emission is proportional to an integral of the dust temperature T_d over the mass distribution of the dust. If a single value of T_d dominates, we have

$$L_\nu \propto M_d T_d, \tag{3}$$

where M_d is the total dust mass and where the proportionality constant (essentially the dust emissivity) is a function only of the bulk optical constants of the grains and not of their sizes (if the grain radii are small in comparison to the wavelength). Since L_ν can be measured and T_d can be modeled, equation (3) allows a straightforward deduction for M_d, from which one can obtain M_g if one assumes a (standard) ratio for the gas to dust. The procedure sounds foolproof; however, one must remember that interstellar dust emissivities at submillimeter and millimeter wavelengths are not yet perfectly known; residual uncertainties of factors of 2 to 3 still exist, although this situation should improve with time as better empirical calibrations are established.

Until these calibrations are available, it would probably be wise to continue to use other methods in parallel with the one above. The CO method commonly assumes that the luminosity in the ^{12}CO line is proportional to the total amount of (molecular) gas:

$$L_{CO} = C_1 M_g, \tag{4}$$

where C_1 is a constant whose value can be obtained by calibration on nearby clouds. The question has been raised at this conference how it is valid to use optically thick radiation to estimate masses. On the face of it, this criticism sounds devastating. However, a good defense exists for the procedure; indeed, the technique did not originate with CO observers – optical astronomers use radiation from optically thick objects to estimate masses all the time! Stars like the Sun have a total optical depth of about 10^{12} through their centers, yet this does not prevent optical astronomers from gathering the integrated starlight from a galaxy to estimate its mass. What is needed, of course, is a calibration of the *mass to light ratio*, *i.e.*, the notion that in some sense one is counting stars of a common population of types. Similarly, if one is *counting clouds* of a fixed population of types, the use of equation (4) is justified. However, variations of C_1 (with gas temperature T_g, etc.) cannot be easily discounted.

Checks for the CO procedure do exist for the Milky Way. As discussed by Phil Solomon, the masses $\mathcal{M}$ of individual giant molecular clouds (GMCs) can be obtained both by the above conversion procedure and by application of the virial theorem. Within factors of 2 or so, the results seem in good agreement:

$$\mathcal{M}_{CO}^{GMC} \approx \mathcal{M}_{V.T.}^{GMC}. \tag{5}$$

In external galaxies, an indirect check exists in Judy Young's work. She finds a correlation between the total far infrared emission (not decomposed in the manner described earlier) and the CO emission of the form:

$$L_{IR} = C_2 L_{CO}^{\beta}, \tag{6}$$

where the exponent β is a pure number with a quoted range between 0.8-0.9 and C_2 is a constant for galaxies of a certain type. She also finds that the types of galaxies ("normal," "starbursts," ...) can be separated out in bands in the $\log(L_{IR})$-$\log(L_{CO})$ plane according to their dust temperatures, *i.e.*, C_2 is really a function of T_d. This conclusion, I believe, worries a number of people, for if the characteristic dust temperature T_d can vary from galaxy to galaxy, why not the characteristic gas (CO) temperature as well? In other words, is C_2 really a function of T_d, T_g, and yet other variables? How does this affect the determination of the exponent β? Despite these reservations, I believe everyone can agree that the observed systematic displacement of "starburst" galaxies from "normal" ones (as classified by other techniques) in the $\log(L_{IR})$-$\log(L_{CO})$ plane is reassuring.

The substitution of equation (4) into equation (6) yields the correlation

$$L_{IR} = C_1^{\beta} C_2 M_g^{\beta}. \tag{7}$$

The indirect check on the whole procedure arises by noting that β is close to unity, which suggests that for a given galaxy type (given C_1 and C_2), the total star formation rate ($\propto L_{IR}$) is (almost) linearly proportional to the total amount of molecular gas M_g, *i.e.*, star formation occurs (almost) independently in individual molecular clouds. The reasonableness of this conclusion speaks in favor of the CO method for determining gas masses; however, it should be noted that the argument is somewhat flawed by the result that the best fit for β is not unity and by the possible variability of C_1 and C_2. As I shall argue toward the end of my summary, in some of the more extreme starburst galaxies, the CO observations cannot be counting molecular clouds – at least not of the variety with which we are familar in the Milky Way. In any case, within the context of equation (7), the issue of enhanced star formation efficiencies manifests itself in the need for the net coefficient $C_1^{\beta} C_2$ to be a factor of 4 to 5 larger for "starburst" galaxies than for "normal" spirals. Given the uncertainties inherent in the various calibrations, I personally am unsure how seriously to take the implied interpretation that starbursts have a star formation efficiency "only" a factor of 4 to 5 larger than normal galaxies. The ratio $L_{IR}^{OB\,sf}/M_g$ could be appreciably larger than 4 to 5 if $L_{IR}^{OB\,sf}$ virtually equals the total L_{IR} in starbursts but is only half of L_{IR} in normal galaxies, and if M_g has been systematically overestimated in the former because the gas temperatures T_g are higher than in the latter.

The gas mass deduced for the central kpc of some of the most active starburst candidates is so large in some extreme cases ($\sim 10^{10}\ M_{\odot}$) that it should dominate the gravitational field of the region. Since the gas likely forms a rotating disk, rotation curves from resolved H I or CO studies may yield good values for the total mass contained in the nuclear regions. It would be useful to compare such dynamically derived masses with the very large estimates for M_g that result from application of the techniques discussed above.

TRIGGERS OF OB STAR FORMATION

Another major area addressed by this conference was the discussion of mechanical triggers of OB star formation. Scoville and Kaufman talked about the effect of *spiral arms*; Devereux and Lo talked about *bars* and *oval distortions*; and a large number of speakers talked about *interacting galaxies*. In the last case, as Alar Toomre reminded us, there are a number of different levels of interactions. At the lowest level, there are gravitationally induced *orbit crashings*; at the next level, there are *thefts* of the fuel for star formation or nuclear activity; and at the most violent level, there are *mergers*. The common underlying theme in all of the proposals seems to be the idea that if one somehow gathers enough gas in a confined space, there will be enhanced OB star formation: the better this is done, the more spectacular will be the resulting starburst.

While this intuitive idea has considerable merit, and the empirical evidence for some sort of effect now seems overwhelming, a few words of caution may still not be out of place. The first caveat concerns the role of mergers in making starbursts in the central kpc of a galaxy. Alar Toomre emphasized how the dissipativeness of interstellar gas would enable it to settle deeper than the stellar component in the gravitational potential well of a merger product. However, there may be a more serious difficulty than binding energy, and that is how to get rid of the excess angular momentum in one or a few orbit crossings. Colin Norman gave a formula for angular momentum transport which indicated very short timescales, but it should be noted that his formula works best near resonances, and that his numerical estimate for the drag coefficient γ invoked the observed nuclear conditions of starburst galaxies. Getting all that gas there in the first place is the real problem. Perhaps the resolution of this problem will come from natural selection, namely, that only those mergers involving appropriate combinations of orbits and spins as to give large amounts of gaseous matter with nearly zero angular momenta will naturally produce nuclear starbursts. (With a flat rotation curve, to reach 1 kpc from 10 kpc, matter needs to have cancelled 90% of its specific angular momentum.) The other combinations may give mergers which do not yield nuclear starbursts, and it would be interesting to work out what the statistics of mergers and starbursts have to say on this possibility.

Jay Frogel in his talk likened the large-scale problem of galactic star formation to the study of a "forest." This analogy raises the caveat that it is not at all obvious how the supposed "trigger" of starbirth is supposed to work on the level of the "trees." For example, OB stars are observed to form not just anywhere in Galactic molecular clouds, but only in the densest cores where the ambient pressure in the form of density times temperature, nT, exceeds 10^7-10^8 in cgs units. Think of the Becklin-Neugebauer object, or W3 (OH), as studied by Jean Turner and Jack Welch, if you want to visualize the extreme interstellar conditions under which OB stars are born. It is the formation of these kinds of regions that one must induce if one wants to trigger OB star formation.

The final caveat begins by noting that the subject of starbursts did not begin with the *IRAS* discoveries of infrared-bright galaxies. Zwicky may well have known about the phenomenon in 1937; certainly in the early 1970s, Sargent and Searle were actively calling astronomers' attention to the problem of blue compact dwarf galaxies. Such dwarf galaxies can evidently undergo starbursts, and as Jay Gallagher and Deidre Hunter have frequently emphasized, some of these systems seem to have none of the gravitational trigger mechanisms enthusiastically embraced at this meeting.

BIMODAL STAR FORMATION

An idea implicit to many people's discussion at this conference, but mentioned explicitly only in the talks by Scoville and Montmerle, is *bimodal star formation.* By bimodal star formation, I mean the notion first introduced by Peter Mezger and Lindsey Smith, and subsequently expanded upon by Rolf Gusten, Richard Larson, and many others, that somehow the modes of formation of low-mass stars and high-mass stars are different and take place more or less independently of each other. The idea is intrinsic to many of the papers presented here because starbursts appear to be primarily a phenomenon of enhanced *OB star formation.* Indeed, in many active regions of OB star formation, a normal initial mass function will give an untenable number of accompanying low-mass stars.

From observations of star forming regions in the Galaxy, it is known that the formation of low-mass and high-mass stars take place in morphologically different kinds of cloud cores. In regions like the Taurus or Ophiuchus molecular clouds, the small cores from which low-mass stars form have gas temperatures $T_g \sim$ 10-30 K and visual extinctions $A_V \sim 10^1$-10^2 mag. This is to be contrasted with the large dense cores in giant molecular clouds with gas temperatures $T_g \sim$ 50-100 K and visual extinctions $A_V \sim 10^2$-10^3 mag. Clearly, this morphological distinction deserves investigation as a basis for a physical theory of bimodal star formation.

Considerable evidence has now accumulated that the birth of low-mass stars is not externally triggered. A relatively complete and satisfactory theory exists, in my opinion, for how such stars form. And, as has been shown by Chas Beichman, Charlie Lada, Phil Myers, and their coworkers, there are many *IRAS* sources which look like the theoretical models for low-mass protostars. The remaining empirical question for the issue of bimodal star formation is therefore: Is the formation of high-mass stars externally triggered?

CONSTRAINTS ON STAR FORMATION TRIGGERS

One constraint on the nature of star formation triggers in the context of starburst galaxies is the need for *global simultaneity.* It does not help to make a starburst if one has a mechanism which only works on one molecular cloud at a time; one needs to make *all* (or, at least, a lot) of the molecular clouds go off more or less simultaneously. Providing global timing may be one role (perhaps the primary one) of gravitational mechanisms like spiral density waves, bars and oval distortions, and interacting galaxies, but one still needs to ensure that the relevant processes act quickly enough to produce the conditions necessary for OB starbirths. This may be a potential problem for the random agglomeration picture proposed by Struck-Marcell and Scalo. As long as they stick to one-zone models, they can get impressive bursts of star formation because in a one-zone model everything is the same everywhere and stays well synchronized. As soon as they go to multi-zone models, they encounter difficulties, as has been reported at this conference. The bursts in individual zones lose coherence, and the integrated light does not show impressive variations. Gathering clouds by fast instabilities rather than by random agglomeration may offer a solution to this problem.

There is a more subtle constraint on the nature of star formation triggers when one comes to the microscopic level of individual star-forming clouds. Historically, it was thought that external triggers were necessary because it was thought that stars formed from H I clouds. *H I clouds are not self-gravitating.* Clearly, it would be very difficult to form stars out of gravitationally unbound material; therefore, something seemed needed to compress or to gather H I clouds to bring them to a self-gravitating state.

Currently, it is known that star formation occurs from H_2 clouds. *H_2 clouds are strongly self-gravitating.* Consequently, it is important not to be trapped by an antiquated viewpoint, to be misled by an H I perspective when we live in an H_2 world. In a sense, the original problem needs to be inverted.

The point is that the star formation efficiency in H_2 clouds is observed to be generally quite low; Nick Scoville and others quote an efficiency of $\sim 1\%$ over the free-fall time at the mean density of a giant molecular cloud. Thus, once H_2 clouds have been formed (by whatever mechanism one favors), the main theoretical problem is not how to trigger star formation, but *how to prevent it from happening even faster.* This is the issue, of course, of the mechanical support of molecular clouds. If we understand how this works, the enhancement of star formation efficiency amounts to the *removal* of the natural obstacle to rapid star formation.

SPECULATIONS ON PHYSICAL MECHANISMS

What is this obstacle to rapid starbirth? What supports molecular clouds in bulk against free-fall collapse? The last is a controversial question, but all workers, at least, are agreed on one thing: it is not thermal pressure. Thermal pressure could be important in the cores but not for the cloud as a whole. Another way of saying the same thing is that the Jeans mass M_J, at the average conditions of a molecular cloud, is much less – by a few orders of magnitude – than the cloud mass M_{cl}. This implies, of course, that Jeans mass arguments have less to do with the actual problem of star formation in molecular clouds than generally thought in many theoretical discussions on the subject.

Could the support of molecular clouds be due to turbulent pressure? Many astronomers would answer yes, but I belong to that school of thought – headed by Leon Mestel and Telemachos Mouschovias – which believes that magnetic fields play the dominant role.

Why magnetic fields? First and foremost, unlike turbulence, magnetic fields are not easy to get rid of. Because the universe lacks magnetic monopoles, magnetic fields cannot be shorted out as electric fields can be by electric charges. The longevity of magnetic fields makes them a natural candidate for a resistant obstacle to rapid star formation. The critical mass M_{cr} of conducting fluid that can be supported by a magnetic flux Φ threading it is given approximately by the well-known formula,

$$M_{cr} \approx 0.15\,\Phi/G^{1/2} \sim 10^5\,M_\odot \left(\frac{B}{30\,\mu\mathrm{G}}\right)\left(\frac{R}{20\,\mathrm{pc}}\right)^2; \tag{8}$$

i.e., even a GMC of mass $10^5\ M_\odot$ and radius 20 pc can be supported against its self-gravity entirely magnetically if the mean field strength threading it were 30 μG. The same formula can be roughly scaled to any subclump inside it, so hereafter the subscript "cl" can refer either to "cloud" or to "clump." Equation (8) provides a second reason for believing that magnetic fields can play an important role in cloud support because tens of μG fields are now commonly measured by the Zeeman effect in the denser regions of interstellar space by Carl Heiles, Dick Crutcher, Tom Troland, and their colleagues. Finally, Fred Vrba, Steve Strom, and others have shown by mapping interstellar polarization vectors in nearby dark clouds that magnetic fields are well ordered over the dimensions of the clouds. This provides a third reason to believe that magnetic fields are strong enough, at least in the smaller molecular clouds, to prevent bad tangling by any turbulent velocity fields that may also be present.

Magnetic fields ameliorate the problem of the rotational braking of molecular cloud cores. The acceptance of their reality also has the virtue of making supersonic (but subalfvenic) "turbulence" in molecular clouds explicable. In this picture, cloud turbulence is simply the superposition of many MHD waves with the perturbations of the fluid velocity associated with the waves generally less than or comparable to the Alfven velocity v_A. The idea is that clouds have many sources of chaotic fluid motions (stellar winds, cloud collisions, etc.) which will generate a wide spectrum of MHD waves. However, waves with superalfvenic fluid motions will generate compressive shocks that disspate the waves rapidly. Thus, an arbitrary spectrum will quickly decay mostly to Alfven waves with fluid motions v_f that are Alfvenic or less. There is a tendency for CO observers to see the largest motions because of photon trapping (Peter Goldreich, private communication); therefore, observations tend to select for $v_f \sim v_A$. But it is easy to show from equation (8) that cloud support by magnetic fields near the critical state implies that the characteristic Alfven speeds are of the magnitude needed for virial equilibrium, *i.e.*,

$$v_A^2 \equiv \frac{B^2}{4\pi\rho} \sim v_{V.T.}^2 \equiv \frac{GM_{cl}}{R}. \tag{9}$$

Thus, $v_f \sim v_A$ implies that $v_f \sim v_{V.T.}$, *i.e.*, cloud "turbulence" automatically has a tendency to look sufficient for virial equilibrium. Pushing this line of argument further, one sees that there should even be a rough correlation $v_f \propto \rho^{-1/2}$ if the magnetic field B does not vary strongly from region to region. With B held constant, the critical state is characterized by a constant mean column density (see eq. [10]), *i.e.*, the mean volume density of clouds (outside of cores) will scale as $\rho \propto R^{-1}$. Thus might arise the correlation cited by Phil Solomon: $v_f \propto R^{1/2}$.

For the issues of more immediate concern here, once one accepts the dynamical importance of magnetic fields in cloud support, one can also immediately deduce that there are logically two regimes of interest for the problem of star formation. In the *subcritical* regime, $M_{cl} < M_{cr}$, one cannot trigger gravitational collapse (star formation) by *any* amount of increased external load (external pressure) if Φ is conserved (field freezing) because the mass-to-flux ratio M_{cl}/Φ would remain fixed and subcritical. The problem is that although one may compress the cloud, one also compresses the field B, and the restoring magnetic forces rise in tandem with the increasing gravitational attraction (assuming quasi-spherical compression). To get star formation in this situation, one strategy is obviously to decrease Φ (by ambipolar diffusion) at more or less constant M_{cl}. Ambipolar diffusion, even in a largely neutral medium like a molecular cloud, is a slow steady process, and I have suggested that this provides the mode for low-mass star formation. In this mode, the production of low-mass stars would proceed at a regulated pace virtually independent of external conditions if the condensing cloud cores are well separated from one another.

In the *supercritical* regime, $M_{cl} > M_{cr}$, the cloud's self-gravity can overwhelm the magnetic support *even if the fields were to remain frozen in the fluid.* (But, of course, ambipolar diffusion would also take place concurrently and hasten the collapse process.) Fred Adams, Susana Lizano, and I have proposed that this forms a natural scheme for getting efficient star formation and/or high-mass stars. The details are vague because the relevant calculations are not yet available, but the general idea is that a supercritical cloud would be able to generate the large, dense, and warm cores evidently needed to produce high-mass stars. It should be noted in this regard, as mentioned earlier and as many people have commented upon before, that the condition $M_{cl} > M_{cr}$ is equivalent to the existence of a critical surface density:

$$\frac{M_{cl}}{\pi R^2} > 80\,\frac{M_\odot}{\mathrm{pc}^2}\left(\frac{B}{30\,\mu\mathrm{G}}\right). \tag{10}$$

The supercritical condition corresponds to the onset of relatively rapid contraction; it gives only a lower limit on the average conditions in a cloud needed to form the dense warm cores that give rise to high-mass stars. Nevertheless, if one were to put even a healthy fraction of 80 $M_\odot$ in a square parsec into O and B stars, one might expect to get areal luminosity densities of $\sim 10^4$-10^5 $L_\odot$ pc^{-2}, which is getting close to that seen in the region of the Trapezium stars in Orion. Fred Lo and his colleagues reported limiting areal luminosity densities of $\sim$ 10^5 $L_\odot$ pc^{-2} for starburst galaxies. Does this number owe its explanation to the existence of a critical surface density needed by self-gravity to overwhelm cloud magnetic fields of a plausible mean strength?

For a canonical gas to dust ratio, equation (10) is equivalent to a critical mean visual extinction:

$$A_V > 4\,\mathrm{mag}\left(\frac{B}{30\,\mu\mathrm{G}}\right). \tag{11}$$

The figure 30μG may typify the average conditions only in relatively small dark clouds; GMCs, and especially their dense cores after gravitational contraction, may well have considerably larger values. Thus, it is interesting to note the following observed progression:

(a) The Taurus molecular cloud has cores with $A_V \sim 10$ mag; it is a region of low star-formation efficiency and seems to be forming an unbound association of low-mass stars.

(b) The densest portion of the Ophiuchus molecular cloud has cores with $A_V \sim 10^2$ mag; it has a high star-formation efficiency and may be forming a bound cluster containing mostly low-mass stars but also a B star or two.

(c) Massive GMCs have large dense cores with $A_V \sim 10^3$ mag; these sites produce an abundance of OB stars.

To complete the conjecture, however, we must specify how the supercritical state is ever reached. After all, if one started initially with a distribution of clouds, some supercritical and some subcritical, one would imagine that all the supercritical ones would quickly collapse on a magnetically diluted timescale. How does one then proceed today to get clouds with $M_{cl} > M_{cr}$ from a collection whose members all have M_{cl} less than M_{cr}? The answer may be simple: the build-up of M_{cl} by agglomeration. Consider two identical clouds (either H I or H_2) suspended on parallel sets of field lines. If these two clouds collide head-on *across* their average field directions, in the aggregate, M_{cl} would have doubled and so would have Φ. Thus, there has been no gain on the critical mass-to-flux ratio. Now consider colliding two identical clouds head-on *along* mutually shared field lines; M_{cl} would again be doubled but Φ would remain the same. There has now been a gain on the critical mass-to-flux ratio. Although the examples considered are idealized, a little thought shows that even random agglomerations will tend to increase the ratio M_{cl}/Φ, and therefore, (portions of) very large aggregates are likely to become supercritical sooner or later. Is this the reason that OB stars tend preferentially to be formed from the largest GMCs?

The same train of thought reveals that the quickest route to achieving supercritical conditions is not to gather clouds randomly, but to gather them *along* field lines (perhaps by the action of instabilities triggered by the gravitational mechanisms described previously). Is this the route to trigger coherent waves of OB star formation and starbursts? Clearly, more investigation is needed. What has been put forward here does not constitute a real theory so much as a suggestion of a possible physical approach to a complex astronomical problem.

A FEW RANDOM OBSERVATIONS

Let me end my summary with a few random observations. First, if it is true that some extreme starburst galaxies have 10^{10} $M_{\odot}$ in the central kpc, then the mean surface mass density must be

$$10^{10}\,M_{\odot}/\pi(1\,\mathrm{kpc})^2 \approx 3000\,M_{\odot}\,\mathrm{pc}^{-2}, \tag{12}$$

which is as dense as the densest regions of the Ophiuchus molecular cloud. Unless molecular clouds are packed several deep in the vertical direction of the nuclear disk (which is difficult to sustain mechanically), there is no room in the central regions of these galaxies to store molecular clouds of the type with which we are familar in our own galaxy. We cannot be counting ordinary molecular clouds in these extreme cases, and the use of equation (4) in its standard form (constant C_1) cannot be correct in principle.

Second, efficient star formation under the condition described by equation (12) is quite plausible if we judge from the example of Ophiuchus. If, unlike Ophichus, numerous OB stars are also formed (perhaps because of higher intrinsic gas temperatures in the cores), then feedback from vigorous star formation under very cramped quarters will undoubtedly play an important role, as has been alluded to by Tim Heckman and others at this conference. Unfortunately, rigorous consideration of all the relevant effects is likely to be quite complex – the feedbacks on star formation itself could be negative as well as positive. Solid theoretical progress will be difficult; this aspect of the field may long remain primarily an observer's domain.

Finally, we should not forget the blue compact dwarf galaxies. How do starbursts work in them? Perhaps a clue exists in their not possessing much differential rotation. According to present ideas, a body undergoing only solid-body rotation will not amplify magnetic fields via dynamo action. Could dwarf galaxies possess anomalously low magnetic fields so that they lack this natural inhibitor to rapid star formation? Or is H I gas, after all, the principal reservoir for forming stars in such galaxies? Or is the constraint of global simultaneity relaxed for dwarf galaxies because the total number of cloud complexes is small enough to allow statistical fluctuations to play more of a role? Clearly, more discussion is needed of these enigmatic objects. They may provide a clue to the problem of primordial star formation, which probably took place in a high temperature environment free of magnetic fields.