SUMMARY

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Nine years have passed since the last IAU symposium on the topic of star formation (1). Research in this key area of modern astronomy has been and remains very active, as can be seen from the number of participants (~ 245 from 18 countries, compared to ~ 161 from 18 countries in 1976), and from the impressive number of interesting papers and posters presented at this meeting (24 invited and 30 contributed papers and 200 (!) poster presentations). The past decade has seen the advent of new techniques of great importance to investigations of stellar birth and infancy: the development of infrared and submillimeter astronomy, and spectroscopy in particular, and the introduction of arcsec resolution imaging of microwave molecular line emission and absorption with interferometry. One of the reasons for our meeting here in Japan, of course, has been the "birthday celebration" of Tokyo University's impressive Nobeyama millimeter observatory which we had a chance to visit during this week.

I will not and cannot attempt to give a complete review of all that has been said and shown in the last four days. In the following, I will instead discuss the results of this meeting in the light of ten main questions about stellar formation listed in Table 1, in order to see where we stand, what we have learned and where we have to place our emphasis in the future. I apologize to those whose contributions I have inevitably overlooked or mispresented.

TABLE 1

Ten Questions About Star Formation

I. What is the relationship between molecular clouds and star formation?
II. What is the kinematics and support of molecular clouds?
III. Are molecular clouds in spiral arms?
IV. What is the rate, efficiency and initial mass function of star formation?
V. What are the dynamical importance of magnetic fields?

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VI. Where are "protstars" and prostellar disks?
VII. How do protostellar clouds collapse and fragment?
VIII. How do protostars evolve toward the main sequence?
IX. What drives the mass outflow in young stars?
X. What are the characteristics of star formation in external galaxies and what are star bursts?

I have deliberately left out in Table 1 such important problems as the structure and dynamics of the interstellar medium as a whole and the formation of galaxies. These questions have been little touched on during this meeting.

I. Relations Between Clouds and Young Stars. There is now abundant evidence that stars form at the dense cores of molecular clouds. Molecular clouds contain most of the mass of interstellar matter in our galaxy and very likely in most external galaxies. Molecular material in the disk of our galaxy is clustered in giant molecular clouds (GMC; $M \sim 10^5\ M_\odot$, $< n_{H_2} >$ a few 10^2 cm^{-3}, $D \sim 50$ pc, $T \sim 10K$). GMC's are probably not a homogeneous group, but there is likely a range of temperature and mass. Evidence has been presented that there are many "small molecular clouds" which are somewhat colder ($T < 10K$) and less massive ($\leq$ a few $10^4\ M_\odot$) than the standard GMC's. Molecular clouds in the central 1 kpc of our galaxy appear to be much warmer, more massive and of higher velocity dispersion than in the disk. GMC's may cluster in "super clouds" of mass $\gtrsim 10^7\ M_\odot$.

The characteristics of dense star forming cloud cores are different for typical low mass (dark cloud) and typical high mass star formation regions. Observations of the 1.3 cm inversion transitions of NH_3 indicate that dark cloud cores (diameter ~ 0.1 pc) are quiescent ($\Delta v_{FWHM} \sim 0.3$ km s^{-1} ~ $\Delta v_{thermal}$ (T = 10 K)), have hydrogen densities of $\sim 10^4$ cm^{-3} and masses of ~ 1 $M_\odot$. Cloud cores associated with OB star formation have been investigated with NH_3 transitions, mm and submm lines of heavy molecules such and with as CS, HCN, H_2CO, and with measurements of the submm dust continuum. The cloud cores (diameter 0.1 to 1 pc) are warm (50 to 100 K), massive (density 10^6 to 10^7 cm^{-3}, mass 10^2 to 10^4 $M_\odot$) and have high, superthermal velocity dispersions ($\Delta v \sim 5$ km s^{-1}). The high activity and clumpiness in the massive cores is probably caused by OB stars which have recently formed there and are now visible as compact IR sources or HII regions.

II. Support of Molecular Clouds. Unless kinematically supported, the ~ 4000 GMC's in the galaxy would collapse in $t_{ff} \sim 10^6$ y, implying an overall star formation rate of a few 10^3 $M_\odot$ y^{-1}. This is three orders of magnitude larger that tne measured rate (see IV): GMC's must be supported internally. The required kinetic energy is in fact present and is evident in the line spectra as supersonic line broadening ($\Delta v \sim 5$ km s^{-1}). It is now clear that the line widths are not dominated by large scale motions, such as rotation or expansion, but are random in nature. In the massive cloud cores, the profiles may be caused by the macroturbulent motions of a number of clumps.

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There is also evidence for rotation in dark cloud and massive cloud cores. Arguments have been presented at this meeting that the turbulence is fed and maintained by differential galactic rotation, by stellar winds and supernovae, or by mass outflows from young stars. No agreement as to the dominant source--if there is any--has emerged. Furthermore, the supersonic motions should decay in a given region on small time scales (~ 10^5 y) due to shock dissipation, unless the propagation of Alfven waves ($\Delta v_{turb} < v_{Alfven}$ ~ 10 km s^{-1}) can mediate the motions and decrease the dissipation rate. In this case the magnetic field clearly must be dynamically important for cloud support.

III. Molecular Clouds and Spiral Arms. The question of whether or not molecular clouds are concentrated in spiral arms has been a matter of heated debate in the last 10 years. A consensus seems to emerge now: The answer may be a clear "yes and no" or "both." Evidence has been presented that about half of the molecular mass in our galaxy is contained in warm, massive GMC's near spiral arms, and half is in colder, lower mass "small molecular clouds" (see I.) which are found everywhere in the disk. Recent single dish and interferometric CO observations give similar results for the molecular material in the grand design spiral galaxy M51.

IV. Rate, Efficiency and IMF of Star Formation. Little news has been presented on the first point, and the publications of Mezger (2) and Scalo (3) still appear to be the standard references (total star formation rate in the galaxy ~ 5 to 10 $M_\odot$ y^{-1}). A promising new development in this area is the infrared work (ground-based and IRAS) which allows for the first time investigations of stellar luminosity functions in very young, optically obscured clusters (Taurus, Orion, ρ-Oph etc.). Star formation is inefficient (mass conversion efficiency less than a few percent) in most cases (unbound associations), with the exception of bound clusters (several 10's of percent efficiency. We have heard two explanations. First, the efficiency may be controlled by the gas removal rate. Observations suggesting that the clouds intially are in virial equilibrium. The fate of the forming cluster, that is, the conversion efficiency into stars and the cluster's total energy, could be entirely determined by the time at which (massive?) stars form which can dissipate the remaining gas with winds, HII regions and supernova explosions. If that time is short, an unbound association results, if it is long, a bound cluster. A second explanation is based on the ratio of the cloud mass M_{cloud} to the critical mass M_{cr} which can be supported by the magnetic field (see VII). In this picture, a high star formation efficiency is only possible in the rare cases where $M_{cloud} > M_{cr}$ (magnetic field dynamically not important).

Evidence has been accumulating for a long time that low mass and high mass stars form in different places. To mention just two arguments: van den Bergh and Walker showed twenty-five years ago that the IMF of young clusters has an excess of high mass stars compared to

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the field. More recently, models of the chemical evolution of the galactic disk--incorporating data on the galacto-centric distributions of light and heavy stars inferred from optical, infrared and radio observations and on galactic abundance gradients--strongly suggest that star formation is "bimodal".

As Herbig emphasized in his summary nine years ago (1), it is the heavy stars which need special conditions for their formation. We know that low mass stars form in dark cloud cores like Taurus-Auriga and it is likely that they form in massive clouds associated with OB star formation as well. This brings up the question of triggering mechanisms. Once an OB star has formed as result of favorable conditions in the cloud, it may trigger further formation of massive stars in its neighborhood, or it may destroy and disperse the cloud. We have heard theoretical and observational arguments in support of both points of view. The undisputed observational fact is that in a number of regions (Orion, W3, M17, etc.) a new generation of massive stars has formed in the vicinity (0.1 to 1 pc) of an older, visible OB cluster, suggesting a causal sequence. There is also ample evidence that the OB stars heat, compress and stir up the gas near the boundary of the dense cloud. A famous case is M17, where recent infrared, submillimeter and millimeter spectroscopic observations clearly show dense warm and hot, shock excited molecular gas along the interface to the M17 OB cluster. It is not obvious, however, how globally important sequential star formation is for the formation of all OB stars. Far-infrared observations have indicated that at least early B stars form throughout the M17SW molecular cloud at large distances from the M17 OB cluster.

Compression by spiral density waves is another triggering mechanism which has often been proposed. We have heard a provocative suggestion about the actual effect of the density wave shock on star formation. All that the density may be doing is to compress clouds and collect smaller clouds into larger (GMC) cloud complexes. The overpressure of the density wave shock by itself is probably not large enough for directly triggering formation of stars. The probability of forming one or a few O stars in these larger complexes simply is larger than in interarm regions. Once a few O stars have formed, massive star formation then percolates along the spiral arm, leading to the familiar picture of giant HII regions/O stars along a spiral arm like a string of pearls. This idea should be tested by new observations.

V. Importance of Magnetic Fields. To the delight of some and the possible dismay of others, evidence is accumulating that, in most cases, magnetic fields are dynamically important in molecular clouds, protostellar collapse and protostellar evolution. We have heard that magnetic field strengths, measured now for the first time in large scale, molecular cloud structures from the Zeeman splitting of the 1.7 GHz OH transitions, scale proportional to $n_H^{1/2}$ from interstellar densities ($n_H \sim 1$ cm^{-3}, B ~ a few μG) to dense OH masers ($n_H \sim 10^7$

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cm^{-3}, B ~ a few mG). The thus derived magnetic field energy density is comparable to or greater than thermal, turbulent and gravitational energy densities in clouds and protostellar envelopes. The important role of magnetic fields is also supported by the large scale alignment of optical and near infrared polarization in several clouds, and the approximate large scale alignment of the flow directions of bipolar outflows with the magnetic field in one region. Theoretical calculations presented at this meeting emphasize the role of magnetic fields in protostellar collapse (see VII) in the solution of the angular momentum problem (losing 3 to 4 orders of magnitude of angular momentum between the cloud and stellar stages) and in the driving of bipolar mass outflows (VIII).

VI. Where are the "Protostars" and Protostellar Disks?

"Protostars" in the sense of pre-main sequence stellar condensations whose luminosity is derived from accretion alone, have been the subject of intense searches and investigations every since Larson's (1969) collapse calculations (4). In some respects, progress in the past ten years has been backwards, since there were plenty of protostellar candidates in the mid seventies, and few are left now. The original hopes came from the dust shrouded appearances of the Becklin-Neugebauer object in Orion and other compact mid-infrared sources. The hope in identifying BN-type objects with Larson's protostars was shattered by infrared spectroscopy which found ionized gas (e.g. hydrogen recombination lines), very hot (a few 10^3 K) and dense molecular gas (e.g. vibrationally excited CO "bandhead" emission), much of it outflowing, but no evidence for accretion. Much the same was seen toward other compact infrared sources, suggesting that the central stars are already hot and that their luminosity is fueled by internal energy sources. In other cases (in Orion), compact infrared sources on 2 to 30 μm maps were shown to be dust condensations (without luminous internal heating sources) which scatter and absorb/reemit the radiation from the two dominant sources, BN and IRC2. Alas, no protostars. The failure to find the elusive protostars may have had three reasons. First, accretion and outflow phases may occur simultaneously. Second, the most detailed (spectroscopic) investigations have focussed on luminous, massive stars. The premain sequence evolution lifetime of such objects is short ($\lesssim 10^5$ y), and the probability of finding them at that stage is correspondingly low. Third, true protostars may be so heavily extincted that they may be below current detection limits even at 10 to 20 μm. I remind you of the case of W51MAIN which is behind ~ 1000 magnitudes of visual exctinction.

How then can we hope to find the dense, accreting condensations, corresponding to the earliest phases of stellar formation? In my opinion, the greatest chance lies in high spatial resolution observations in the submillimeter, where emission lines of heavy molecules (HCN, CS etc.) may give unambiguous evidence for warm (~ 100 K), very dense (> 10^7 cm^{-3}) gas, and where dust emission is most sensitive to large column densities. Identification of protostellar

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condensations from mm line observations is more difficult because of radiative transport effects in foreground gas and because warm, dense gas has a large value of the partition function. The spreading of the population over many levels makes low-J value transitions weak relative to extended, low temperature and low density gas. We have ssen a very nice example of this effect in a $C^{18}O$ J = 1→0 map of Orion which shows no outstanding peak in the BN-KL region, despite the large peak in column density, temperature and density which is known to be present there. The experience of the past ten years teaches us that the near and mid infrared continuum of dust may not be specific enough to learn much about protostars even if increased sensitivity may overcome the extinction problem. If there is enough sensitivity, infrared spectroscopy of a candidate protostar may be the most valuable tool for detailed investigations of physical conditions.

What about disk structures which are predicted to surround newly-formed stars by most theoretical models? We have heard at this meeting that an elongated dust and gas cloud of planetary mass around the T-Tau star HL-Tau is inferred from near infrared (dust scattering) and 3 mm (thermal dust and gas emission) observations. The stars β-Pict and L1551 IRS5 may be other examples. Compact and in some cases flattened structures have also been found in mm line studies of several sources (Orion, L1551, CepA, NGC7538, S106, G10.6-0.4, K3-50). Some, although by no means conclusive, evidence for rotation has been presented. There are two main problems. First, the spatial resolutions currently available for single dish (~ 20") and interferometric studies (~ 5") are still to coarse to truly probe the relevant scales. At a distance of 1 kpc, 10" corresponds to ~ 10^{17} cm (10^4 Au). A disk of that diameter around a 10 $M_\odot$ star has a rotation velocity of only 1 km s^{-1}. Second, detailed single dish and interferometric observations of the Orion-KL core have now convincingly demonstrated that chemistry may dominate the appearances of the spatial distribution of different molecular lines. Maps of several molecules, combined with infrared and millimeter continuum maps may be required to determine fully the spatial distribution and kinematics of material around a newly formed star.

VII. Collapse and Fragmentation. Much progress has been made in the past decade in more realistic, two and three dimensional calculations of stellar collapse. Rotation and magnetic fields have been included. Semi-analytic calculations presented at this meeting indicate that for $M_{cloud} \lesssim 10^3 M_\odot B_{30\mu G} R^2_{2pc}$ the magnetic field is dynamically important. Collapse and fragmentation is them quasistatic and is controlled by ambipolar diffusion of the field with $M_c < M_{cr}$. In the framework of a slowly rotating, contracting isothermal sphere, the results are solely determined by the assumed accretion rate. With reasonable accretion rates (10^{-6} to 10^{-5} $M_\odot$ y^{-1}), the models can account successfully for the birthline positions (L, T_{eff}) of T-Tau stars and for the spectra of IRAS sources embedded in the Taurus dark clouds.

The scenario of fragmentation in a rotating cloud is likely somewhat different from the classical hierarchical picture (Hoyle) based on the Jeans criterion in spherical isothermal clouds. First, the most rapidly growing mode in the Jean's instability has the largest wavelength. A rotating and collapsing cloud, therefore, first forms a thin disk and then a filamentary structure before it can fragment further. Analytical and numberical investigations of rotating isothermal clouds suggest that fragmentation can only occur if the product of $\alpha = E_{therm}/E_{grav}$ and $\beta = E_{rot}/E_{grav}$ is less than about 0.1. For $0.2 \gtrsim \alpha\beta \gtrsim 0.1$ there is collapse but not fragmentation, for $\alpha\beta > 0.2$ there is no collapse. In contrast to the Jeans instability in spherical clouds, the fastest growing mode in the collapse of two dimensional structures (disks or filaments) has a finite (non-zero) wavenumber, resulting in a typical mass scale M_0 for fragmentation. The mass scale M_0 is very sensitive to the temperature of the gas ($M_0 \sim T^{\delta}$, $\delta \sim 2$). This result suggests an obvious connection to the idea of "bimodal" star formation mentioned above (IV): more massive stars form in warmer clouds.

VIII. Evolution of Protostars. Much research ranging from the iadio to the X-ray wavelength bands has been done in this area. The major new result has come quite unexpected: most if not all stars $\gtrsim 1$ $M_{\odot}$ go through a period of mass outflow. The outflows have velocities of about 50 to 200 km s^{-1}, and have an ionized as well as a neutral, molecular component. Most of the mass is in the molecular component, and the derived mass loss rates range from 10^{-8} $M_{\odot}$ y^{-1} (T-Tau stars) to $\gtrsim 10^{-2}$ $M_{\odot}$ y^{-1} (W51, W49). The momentum transported in the flows scales approximately linearly with the luminosity of the source. The observations show that the mass outflows are in most cases not spherically symmetric, but bipolar. The radio data indicate that the molecular outflows are on the average poorly collimated at distances of $\gtrsim 0.1$ pc from the central sources. Measurements in the visible show highly collimated jets close to the stars. The lifetime of the outflow phase has been estimated to be $\sim 10^{5\pm0.3}$ y from the occurence rate of H_2O masers in OB star formation regions, and to be $\sim 10^{4.5}$ y from the dynamical age and occurence rate of CO broad wing sources. These estimates suggest that the mass loss phase may span a significant fraction of the pre-main sequence lifetime of at least the more massive stars. We have heard a plausible scenario where mass outflow starts during the accretion phase (accretion in a disk and outflow along the poles) and terminates when the star has reached the main sequence and becomes visible.

A very satisfying result has been that we have now come to recognize that the mass outflows combine and unify a number of very different observational signposts: optical jets, Herbig-Haro objects (proper motions!), ionized winds (Brα, Brγ, radio continuum), broad wing sources in thermal molecular rotational emission (CO, SiO, HCN, HCO^+), H_2O, OH and SiO masers (proper motions!) and hot molecular and atomic emission from shocks (H_2, CO, OH, OI, etc.). Detailed theoretical work and interpretations of these phenomena have only

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recently started, but probably have already successfully accounted for the hot molecular component by magnetohyrodynamic "C-type" shocks with inferred magnetic fields of about one milligauss. Shocks driven by the outflows are also very likely responsible for the excitation of Herbig-Haro objects and of H_2O masers which may be thought of as moving "bullets" ramming into the surrounding medium. Shock excitation--especially in C-type shocks--is very efficient in converting kinetic energy into infrared and microwave line radiation over extended spatial scales. This may explain why the spectacular phenomena excited by shocks could be easily found and why they often dominate the infrared and microwave line spectra of the star formation regions.

The Nobeyama observations of L1551 suggest that the CO 1→0 lobes arise near the walls of an otherwise low density, cone like cavity. The CO gas may represent material which is swept up by the outflow at ~ 0.1 pc from L1551 IRS5. For the first time clear evidence has been presented for acceleration of the gas at that distance and some--although small--rotation of the entire CO lobe. The walls of the cavity also act as "mirrors" which reflect the visible light from the central source and give much imformation on the material within a few arcsec of IRS5.

Observations of H_2O and SiO masers indicate that the molecular flows are fully established within 10^{15} to a few 10^{16} cm of the stars. Optical observations and measurements of infrared hydrogen recombination lines show that the ionized components of the flow are present within ~ 10^{14} to 10^{15} cm from the star. The velocities of the ionized flows are somewhat higher (a few 10^2 km s^{-1} rather than a few tens of km s^{-1}) and the momentum transport rates smaller than in the molecular component, however, so that the relationship between the two is at present not clear.

IX. What drives the Outflows?. While the phenomenology of the outflows seems to be well in hand, we know little--observationally as well as theoretically--about the mechanisms driving and collimating the flows. There is general consensus that simple radiation pressure driven winds (as in O stars or post main sequence giants) will not work, since the momentum in the outflows exceeds by far the momentum of the radiation field. The mechanical luminosity in the molecular flows is about 10% of the stellar luminosity. Hence, it seems likely that the gravitational-rotational energy reservoir of the protostar and its envelope has to be tapped in order to account for the mass loss. The theoretical ideas/models mostly fall into two categories. The energy is either extracted from the disk (radius ~ 10^{14} to 10^{16} cm), or from the young star itself (radius ~ 10^{12} cm). Since the available energy scales like GM^2/R, the energy of stellar material extracted at the stellar radius is significantly larger than that of disk material extracted at the disk radius. In the "disk models," disks have to be relatively massive ($\gtrsim 10\ M_\odot$) to account for the observed flow energies (10^{45} to 10^{48} erg). We have seen several

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interesting models of both kinds described during the meeting, but I don't think that general agreement has been reached yet. In all the models we have seen here, magnetic fields play an important role in the acceleration and collimation of the flows. Other focussing mechanisms have been proposed which involve large scale (0.1 pc) structures (e.g. large scale "toroids"). However, such models appear now less attractive, since the flows probably are already collimated at smaller distances from the stars and since it is questionable whether there is enough material in these structures to be dynamically important.

X. Star Formation in Other Galaxies. The IRAS satellite and recent progress in ground based and airborne facilities and instrumentation have made possible the first extensive studies of molecular material and infrared emission in star formation regions in external galaxies. Observations of a number of spiral galaxies indicate an excellent correlation (over 4 orders of magnitude) between far-infrared (~ bolometric) luminosity, CO 1→0 line luminosity and cm radio continuum luminosity. Assuming that CO luminosity is proportional to molecular mass with a constant, global proportionality factor (empirically determined in the disk of our galaxy), the star formation rate (~ far-IR luminosity) per nucleon and supernova rate (cm continuum) per nucleon of interstellar matter is inferred to be approximately constant. The star formation efficiency would then be a global invariant, suggesting that star formation is a local process which is little influenced by the global environment (e.g. strength of spiral density wave, disk vs. nucleus, Hubble type). This first order picture probably has to be refined, however. Recent far-infrared and mm spectroscopic measurements in several galaxies and optical observations of the Magellanic Clouds indicate that the character of the interstellar medium is significantly influenced (i.e. heated, compressed and disrupted) by the star formation process itself. The most dramatic evidence has been presented for the "star burst" galaxy M82, where the observations show that the interstellar gas in unusually warm and dense and molecular gas complexes are lifted to large scale height above the plane (~ 200 pc). For a given bolometric luminosity, the CO luminosity also appears to increase with dust temperature. The molecular emission in most galaxies shows a strong peak at the nucleus which is also the peak of the energy density. All these facts suggest that the star formation efficiency can be significantly smaller or larger than the average value, depending on the environment.

The most extreme cases of these deviations, of course, are "star burst" galaxies which have been the subject of much attention in the past five years. In these galaxies star formation rates are elevated by up to two orders of magnitude over the values typical for normal spiral galaxies. Hence, at the present star formation rate, their gas reservoirs would be exhausted in 10^7 to 10^8 y. The observations suggest that mostly high mass stars and few solar type stars are formed in star formation bursts. Evidence has been accumulating that

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the bursts are triggered by tidal interactions with companion galaxies or by bars. Star burst galaxies have generally been identified by their blue colors in the visible (Markarian galaxies) or by their large far-infrared luminosities. The correlation between high far-infrared luminosity and the star burst phenomenon may not be one to one, however. For example, Arp 220 and NGC 6240, two of the most luminous infrared galaxies (L_{IR} ~ a few 10^{12} $L_{\odot}$) have been interpreted as prototype star burst galaxies, but several observed characteristics (lack of strong Brγ and Brα emission, very strong H_2 2 μm line emission, and small size) suggest that energy sources other than star formation may account for the large infrared luminosity. It is clear that much future work will be necessary to get a better understanding of the star formation burst phenomenon.

In summary then, where do we stand, where can we place our check marks and where should we direct our emphasis in the future? In my opinion, we know now quite a bit about points I, III, and VIII. We have also learned much--but certainly not enough--about II, IV and V. We know still too little about VI, VII, IX and X.

It seems to me that one of the most important goals of the next 5 to 10 years should be to learn more about the young stars and protostars themselves. With the tools of infrared spectroscopy and high spatial resolution imaging we should aim to construct the infrared equivalent of a Hertzsprung-Russell diagram of newly formed stars. Let me also suggest to the theorists that realistic models which can be directly tested by observations--of which we have seen some at this meeting--are extremely important and urgently needed on all fronts of the field.

Finally then, let us all thank the organizers of this IAU symposium for an extremely stimulating and interesting, and very well organized meeting. I would like to thank Mark Reid for many helpful discussions.

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