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CONCLUDING REMARKS

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It is a great honor to be asked to summarize a conference such as this one, but it is also an impossible task. For a summary I refer you to the table of contents; what I will do here instead is to offer some personal impressions of what we have been doing.

My initial feeling was that of an outsider; I have never worked in the field of double and multiple stars, to which many of you have devoted your careers. Yet this meeting has impressed me with the interrelationship of our areas. In this room are astronomers who represent and have discussed celestial mechanics, stellar dynamics, stellar spectroscopy, and the astrophysics of star formation. I have not counted heads, but we outsiders might even outnumber you hard-core binary-fanciers. And this is, in some sense, a measure of the value of this meeting, and, even more pointedly, of the value of your work: how much does it matter to the rest of us? Every astronomer should ask himself —particularly when the technicalities get thickest— "What am I doing this for?" The answer is emphatically not merely that this particular work is interesting to do. The appeal of astronomy is not in the bricks and mortar that each of us prepares, but rather in the architecture of the structure that we build with those materials. The questions that we really pursue are not the orbits of binaries, nor the structure of star clusters, but rather the basic problems of the universe: how and why are stars made, and why do they develop as they do?

In taking a generalist's view about this conference, however, I should not in any way detract from the importance of the fundamental data that binaries provide. No astronomer should ever forget that the painstaking study of binaries has always been nearly our sole source of stellar masses, and that without it we could never have entered the modern era of astronomy. (Let us also not forget the close binaries which give us stellar radii and precious astrophysical details besides.) And with the mass-oriented orbital studies we encounter that tantalizing challenge, of such intense human interest: can we discover planets that go around other stars?

This last question touches upon a more general astronomical problem: what can binaries and other multiple stars tell us about the general ways in which stars and their systems are born? Theories of star formation have always been plagued by the problem of where to put the angular momentum, and the creation of a binary is one obvious solution to the dilemma. Thus it is of the greatest importance to know the frequency of binaries and the distribution of their separations. Here I am impressed by the very large fraction of stars that turn out to be binary, when you look at them carefully enough. In fact, this same remark seems to apply even to stars that are themselves components of wide binaries; a large fraction of them turn out to be close binaries. Has such a system encountered the angular-momentum problem more than once and solved it by repeated division into a binary hierarchy? Could it be possible, in fact, that there is no such thing as a single star, devoid of either a companion star or a large planet? This is of course an old idea, but it is still as relevant as it ever was.

In this connection I should like to remind you that from the point of view of star formation the distinction between stars and large planets is a quite artificial one. At the time a protostar first achieves its identity, it has no way of knowing that later rules of astrophysics are going to control admission to the stellar club. The future stars are only those protostars whose mass is greater than the magic minimum of 0.08 $\mathcal{M}_\odot$ that is needed to turn on hydrogen burning. The lower-mass fragments fail to achieve this elite status, but they do not leave the scene; instead they cool into "brown dwarfs", radiating away the internal heat with which the inevitable workings of the virial theorem briefly endow them. Jupiter and Saturn are such objects, and in this sense the Sun is a triple star. The real dividing line is not between luminous stars and large planets, but rather between large planets and small ones. Specifically, the distinction that we should make is between those bodies whose composition is largely hydrogen (and presumably helium too) and those in which hydrogen exists only in chemical combination with the cosmically less abundant elements.

This distinction becomes clearer when we consider the smaller bodies of the Solar System. They are composed, each according to his distance from the Sun, of materials that could remain as solid particles in the *present-day* radiation field of the Sun. The outer bodies appear to be CNO ices, whereas the inner bodies are compounds that are based on silicon and the metals. What is most striking is the location of the dividing line, at the distance from the present-day Sun where the ices would evaporate away. Thus the Sun was already shining on the particles that afterward went to make up the smaller planets and the other bodies.

Not so Jupiter and Saturn. There is no reasonable way in which solid or molecular hydrogen could have maintained itself in a Sun-drenched era, to collect into large planets. These two brown-dwarf companions of the Sun must have existed as integral bodies before the Sun turned on. Nor, looking at the problem from a different direction, can we still support the antique argument that a planet like the Earth simply has too low a gravity to hold hydrogen. That argument puts the cart before the horse; a proto-Earth that had hydrogen in the cosmic proportion to our present silicon would be about the size of Jupiter and would have no difficulties in holding hydrogen. The hydrogen must already have been gone before the Earth formed.

Thus, from our own triple star, we contemplate the other objects around us. As I have said, the number of binaries and their distribution of orbit sizes is a question of extreme interest —but I can hardly think of an astronomical problem that is more severely affected by observational selection. The likelihood that a binary will be discovered is affected strongly by its orbital separation and the absolute magnitudes of its components, and reliable statistics are thus very difficult to assemble. (In this connection, I am surprised not to see more explicit use made of a method that has proven valuable at the opposite end of the scale: the V/V_m method that was developed by Schmidt for studying the statistics of quasars.)

In other areas of technique the developments have been most impressive, however. I would single out particularly the method of lunar occultations, about which we have heard a great deal at this conference. Not only does it yield accurate separations of close binaries, and even radii of many stars; I think that in the present context the striking contribution of the occultation method is the discovery of so many binary systems that we would otherwise have no way of observing. This is really exciting. Also of great importance is the introduction of automatic measuring machines for the photographs on which your work is so dependent. Plates can now be measured as fast as they are taken, thus putting the bottleneck where it belongs, at the telescope. It would be tragic if we got the telescope time to pile up a lot of valuable material but were then unable to measure it and produce results. There is a good chance now to clean up the backlog of past years; and with the increased accuracy of the automatic machines, a good deal of the old plate material can profitably be remeasured. Finally I should note the valuable use of photoelectric area scanners for close pairs, and the still-experimental applications of speckle interferometry.

At the same time as we ask about the distribution of orbit sizes of binaries, we should also ask about the luminosity function of the components. Here again, the question is not just data or statisics; the real underlying astronomical questions concern the formation of binaries, and the formation of stars in general. We have heard discussions of the luminosity function here; the data are still incomplete (and again plagued by observational selection), but this is clearly a question that all astronomers will follow with interest.

When we think about the formation of binaries, however, there is an important distinction that we need to make. Some binaries —including all the close pairs— are born by the splitting of a birth event into a pair of protostars; but binaries can also be formed by dynamical encounters between single stars. In the field around us, this is now an event of vanishingly small probability; but it is not at all unusual in a star cluster. Even for field stars it is an important process nevertheless, because it seems likely that stars form in groups, and in the early history of a group there is ample opportunity for the dynamical formation of binaries.

Thus, selective studies of the luminosity function, for close binaries versus wider pairs, may someday shed light on the distinction between the two modes of binary formation. And perhaps we shall eventually have to consider more than two modes; is it plausible that a pair of stars at a 10 AU separation were formed in the same way as a pair that are separated by only a few stellar radii? I am not sure that we are even entitled to ask these questions yet; but it is your work that will make such questions legitimate and, in a later era, lead toward their answers.

The problem of dynamical formation of binaries is, in fact, a marvelous crossroads of astronomy. The problem first appeared in studies of the dynamics of star clusters, but one of its applications is clearly to binary stars, and the techniques involved draw heavily on celestial mechanics. The formation of binaries was an unexpected result of von Hoerner's very first N-body simulation. This blessed new discovery was a curse in disguise, however; the presence of the fast-revolving binary required using such a short time-step that it was no longer possible to follow the main cluster calculation itself. Needless to say, the N-body simulations of clusters now cope readily with the binary problem (after a valuable infusion of the techniques of celestial mechanics), while the study of the binary-forming process itself has become an exciting new area of stellar dynamics. Such are the fruits of serendipity.

In this connection I note with some embarrassment that the area in which the investigation of binaries has lagged the most is in observational studies of star clusters. The N-body simulations predict that binaries should form in open clusters, and that they should involve the most massive and conspicuous of the member stars. Yet no satisfactory study of this question has been made, in spite of the easy availability of the photographs on which it could be done.

In between the star clusters and the binary systems lies the gray area of the systems of small N. I have always considered that star clusters and multiple stars are separated by two distinguishing criteria. First, a cluster can be described by distribution functions of velocity and of density, with individual motions and interactions entering in only a statistical way, through double and multiple encounters. A multiple star, on the other hand, can be meaningfully described only in terms of the orbital motions of the individual stars. Second, if we do look at individual orbits in a cluster, each of them is a slowly changing rose-loop through the collective of all the other stars; whereas the components of a multiple star have a set of binary orbits that are maintained in a rigorous hierarchy.

For most of the range of stellar systems the two criteria are equivalent, but they disagree for one type of system whose astronomical significance is increasing: the erratically behaving small-N systems that we loosely call trapezia. We have heard a good deal at this conference (much of it from our hosts) about the distinction between hierarchies and trapezia, and it is clearly an important distinction. Observationally the trapezia belong to the domain of multiple stars; and since astronomical truth originates with observation, we place them among the binaries. Logically, however, the trapezia are the very-low-N extreme of star clusters. Depending on your point of view, they are unstable multiple stars, or else they are star clusters with very fast escape rates. In either case they are an interesting problem in celestial mechanics; but more important, either point of view emphasizes that trapezia last only a short time, so that whenever we see a trapezium we know that we are dealing with a newborn group of stars. Thus they become vehicles for the study of young stars and of the process of star formation itself.

Here we are again: everywhere we look, we find that our various fields of research are interrelated. If this conference has a theme, this is it. We are all working on the same problems, even though we have different points of view and we use different techniques. Let us maintain contacts such as we have made here; they will help all our work, because at bottom it is all the same work.