# SUMMARY OF THE COLLOQUIUM

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I have rarely had the pleasure of attending a conference in which the sheer volume of information has been so impressive and the contributions have been so diversified. Ordinarily, an I.A.U. colloquium is quite specialized, but this one might easily have been sponsored by half a dozen commissions and several international scientific unions. Astronomers from many sub-disciplines, atomic physicists, plasma physicists, aerodynamicists and applied mathematicians have come together to unite solar and stellar physics and to learn one another's scientific language. In principle, my task is to summarize more than 100 papers, which is clearly impossible even if I had had two evenings to prepare instead of one. The best I can do is to mention a few of the papers which seem to me to have conveyed the flavor of the conference and to ask the forgiveness of the remaining authors.

The idea of using solar guidelines to investigate other stars is an ancient one. In 1905, G. E. Hale gave as one reason for founding the Mt. Wilson Solar Observatory "the investigation of the Sun as a typical star in connection with the study of stellar evolution," and in the year I was born, 1913, Eberhard and Schwarzschild pointed out that the emission reversals of the H and K lines in stellar spectra implied "the same kind of eruptive activity that appears in sunspot, flocculi and prominences." They suggested that the intensities of the emission lines might vary analogously to the sunspot period. These early suggestions could not be implemented immediately because the observational capabilities were lacking. Photographic techniques were too crude, detectors too inefficient, gratings too imperfect and most important, we did not have access to the radio, ultraviolet and X-ray regions of the spectrum.

This conference has focussed on the red dwarf stars, objects at the lower end of the main sequence, which are much harder to observe than their more flamboyant fellows in the upper half of the H-R diagram. They are a unique class of objects because their ages are spread over a

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factor of 100 or more, from those approaching the age of the galaxy to others as young as a few tens of millions of years. This diversity enables us to examine how various important parameters vary with age-rotation, magnetic fields, chromospheric and coronal activity, chemical composition, etc.

A widely used conceptual model for red dwarf stars is closely linked to current ideas on how activity is generated in the Sun. These ideas have crystallized in the last decade, although their genesis occurred much earlier. In giving my impressions of this colloquium, I should like to refer briefly to this model and its solar inspiration.

It is generally accepted that rotation and convection are the principal ingredients in the recipe for magnetic activity in the Sun. First, as Belvedere has described in his thorough and lucid review, differential rotation in the convection zone amplifies a weak, poloidal field by dynamo action. Convection then carries the field to the surface, where it appears in the form of magnetic flux tubes, some of which cluster tightly together to form plages and sunspots. Turbulent, convective motions store some of their energy in the magnetic fields by bending and twisting lines of force, after which a number of possible mechanisms may dissipate the stored non-thermal energy and thereby heat the chromosphere and corona, throw off prominences, and generate solar flares and the solar wind. Energy is lost from closed magnetic regions by radiation and from open regions or coronal holes by mass transport.

The same scenario is extended to other late-type stars on the main sequence by postulating that young stars are rotating rapidly and therefore that magnetic activity with all its consequences is extremely intense. Objects like T Tau and BY Dra may be extreme examples. In some fashion, the magnetic activity generates stellar winds, which carry away angular momentum and put a brake on stellar rotation, resulting in a decrease of activity with stellar age. Close binaries are of special interest because synchronism of orbital and rotational periods causes rapid rotation and excessive magnetic activity on relatively old stars. The RS CVn and W UMa stars are thought to be such objects. We have heard much in this meeting about the behavior of stars in close binaries from Bopp, Catalano, Charles, Dupree and many others.

Clues to the understanding of red dwarfs can also come from the study of red giants and supergiants, in which convection occurs on enormously greater scales and is therefore more easily observed. For example, granules should have typical diameters of a sizable fraction of a stellar radius. Perhaps a dozen convection elements cover the entire surface; temperature fluctuations may be on the order of 1000 K and convective time scales may be 200 days or longer.

Turning now to the subject matter of the colloquium, we were introduced to the red dwarf stars by several comprehensive reviews covering their global and photospheric physical parameters, the properties of their quiescent chromospheres, transition regions and coronae and the methods used to derive them. Petterson showed how the fundamental parameters, L, and $T_{eff}$ can be determined empirically and used in conjunction with calculated evolutionary tracks to infer the evolutionary states of individual red dwarf stars. Masses as low as 0.02 $M_\odot$ have been deduced in this way. The chemical abundances in flare stars appear to be the same as those of other dwarfs and the Sun. Surprisingly, Li has been seen in only one flare star. As in the sun, the detection of oscillations in red dwarfs would give information on the structure of the interior. Periods of 14-60 minutes have been predicted but there has been no positive detection as yet. The detection of oscillations should have high priority. Long periods of observation will be required either from space platforms or perhaps at the South Pole, if the hazards of the Antarctic winter can be dealt with. Paterno and Zuccarello suggested that the depth of the convection zone may be an important parameter in the determination of X-ray fluxes from red dwarfs. It is not yet clear whether or not oscillations with high $\ell$-values, which would give information on the depths of convection zones, can be detected in integrated starlight.

It is now well established that stellar rotation is a fundamental parameter underlying red dwarf activity. Petterson described several methods for inferring rotational velocities, including rotational broadening of absorption lines through the use of cross-correlation techniques, which gives V sin i, and rotational flux modulation by spots (photometric light variations) and plages (Ca + emission intensity variations), which yields equatorial velocities. Binaries tend to rotate faster than single stars and spotted stars much faster than plage stars. A remarkable new technique, called Doppler imaging of starspots, has been invented by Vogt and Penrod. The method gives not only rotational periods, but the sizes of starspots, information on their migration across the star, and, when supplemented by V-R photometry, their temperatures. The method can only be applied to the very fast rotating stars like BY Dra and RS CVn. An important conclusion from the work of Vogt and Penrod is that starspots are not morphologically similar to sunspots - they are quite large, covering up to 20% of the stellar surface and their temperatures indicate they resemble giant umbrae, with little or no penumbrae. In the BY Dra stars, the spots have been found to migrate to the poles where they dissolve into remnants, much like high latitude solar coronal holes, and to exhibit period variations implying differential rotation in the same sense as in the sun. During the past 8 years, Rodono and associates at the Catania Observatory have been studying the light variations of BY Dra and II Peg, from which they have inferred cyclic migration of spots in latitude and lower limits to rates of differential rotation. In the RS CVn stars, the spots appear to migrate in all directions, N or S and E or W. Estimates of the sizes, temperatures and migration rates of spots may also be inferred from photometric measurements. Vogt and Penrod have applied the Doppler-imaging technique in some detail to the RS CVn star HR 1099. The behavior of a spot group on this star was more like that of a solar complex of activity than a sunspot group. Blanco and his collaborators reported the results of twenty years of dedicated

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photoelectric photometry of RS CVn at Catania Observatory. Analysis of the light curves suggests a qualitative model in which huge spotted regions migrate in both latitude and longitude in a differentially rotating star.

Long-period cycles similar to the 11-year sunspot cycle have been found from Ca II emission and from photometric waves. Vogt's compilation of these cycle periods for 11 active, single dwarfs reveals that for $P_{rot} > 7$ days, $P_{cycle}$ is approximately constant at $9 \pm 2$ years. Stars in this category do not appear to show large spots. However, from examination of 6 binaries with $P_{rot} < 7$ days, $P_{cycle}$ was found to be proportional to $1/P_{rot}$ and, moreover, the stars in this group display large, dark spots. This remarkable, apparent discontinuity in the cycle period at $P_{rot} = 7$ days needs to be investigated for a larger sample of stars and would obviously be of great significance if confirmed.

Other than the evidence from the poleward migration of spots in BY Dra stars, to which I have already alluded, no sure evidence of differential rotation in solar-type stars was reported, although Baliunas offered the possibility that the rotation periods derived from Ca II emission intensities might vary with cycle phase. On the subject of Ca II emission intensities, Soderblom cast doubt on the evolutionary significance of the Vaughan-Preston gap in the relation between Ca II intensities and B-V, by pointing out that the intensity is not a linear function of age, and that there is very little difference in the H-K intensities between stars in the Hyades and those in the Pleiades. Catalano and Marilli showed that the K-line emission decays exponentially with the square root of the age.

The key to interpreting stellar activity is the direct measurement of magnetic fields. The Robinson method of deconvolving a Zeeman sensitive line by use of an insensitive line, which yields both the field strength and the area covered by the field, is beginning to be widely used. Marcy, at Lick Observatory, has observed that 10 of 29 G0V - K5V stars have obvious fields in the range 800-1500 gauss. Area filling factors of 60-80% are common. In principle, the Robinson method ought to be applied at the longest possible wavelengths, since the ratio of Zeeman splitting to the Doppler width is proportional to wavelength. For example, the 12$\mu$ emission lines observed in the Sun, by Brault and Noyes, which I have discussed in a contributed paper, would be ideal, but their detectability in other stars remains to be demonstrated.

The enormous areas covered by starspots will not be easy to explain. Where does the energy go? Gershberg told us that the energy of X-ray radiation detected from the quiet coronae of flare stars is comparable with the radiation missing in dark spots. He made the novel suggestion that the energy is converted into hydromagnetic waves which heat the coronae. Mullan suggested that the missing energy is stored in the form of trapped Alfvén waves and that the escape of as little as 1% of the stored energy would provide enough energy to power large solar proton flares.

Quiescent coronae and chromospheres of red dwarf stars have been studied principally with the Einstein and IUE satellites, and the results were summarized here by Golub, Linsky and Johnson. Beginning at late F spectral classes, the X-ray flux increases with increasing rotation rate, as reported by both Golub and Johnson. The M-dwarf coronae are generally much more active than the solar corona, exhibiting greater variability and temperatures up to $10^7$ deg. K. Magnetic fields inferred from X-ray fluxes are also much stronger than in the sun, by one or two orders of magnitude. The fact that the X-ray flux decreases strongly with B-V may imply, as Giampapa has tentatively suggested, that the entire star is becoming convective and that the stellar dynamo has no room in which to operate. New computations on the generation of acoustic energy from convection zones of late-type stars were reported by Bohn, who finds that the flux of acoustic energy from the very cool stars is nearly five orders of magnitude greater than that given by previous calculations. It now seems that more than enough acoustic energy is being generated to account for the X-ray emission of late-type stars but this does not alter the prevailing view that the energy will be dissipated in the chromospheres before reaching the coronas of M stars.

Evidence for red dwarf activity in chromospheres and transition regions, based on IUE data, is beginning to pile up. Linsky emphasized the all-pervasive influence of magnetic fields in his summary, while pointing out that rotational modulation by plages can be seen in transition-region lines. In II Peg, the fluxes in these lines are anti-correlated with the photometric variations that indicate the transit of dark starspots. Stellar plages may be much brighter than in the sun, up to a factor of 50 in the CIV lines. The CIV flux shows variations of up to 70%.

In no aspect of red dwarf research has progress in the past 2-3 years been so dramatic as in the study of flares. Where previously there was a scattering of visible light curves and radio detections, only occasionally simultaneously, there is now a well-coordinated program of observations in visible, UV, X-ray and radio wavelengths and a sophisticated approach to the analysis and interpretation of data based on solar experience. Optical photometry, optical and UV spectroscopy and X-ray and radio data are combining to give a clear picture of the similarities and differences between solar and stellar flares.

Byrne reviewed the morphology of flare light curves and the statistics of times of occurrence of optical flares. Among the interesting questions he discussed were the extent to which the parameters of the light curves can be systematized, whether there is evidence for precursor events and whether there may be periodicities in the occurrence of flares, related perhaps to the rotation period of the underlying star.

The energy released in dMe flares sometimes exceeds that from solar flares by $10^3$. Yet, Worden showed that optical and UV stellar flare spectra are surprisingly like their solar counterparts. A major handicap at present is the cutoff of IUE spectra at 1100 Å. Plans are being drawn to fill the gap between 1100 Å and X-rays. I was pleasantly surprised to learn that EUV radiation, at least below 500 Å, can penetrate the interstellar medium to the sun from most known flare stars.

Gibson and Lang gave impressive demonstrations of the power of the VLA in flare studies. Such parameters as temperature, electron density, magnetic field and emission measure are readily derived and polarization measurements give unique information on non-thermal processes and mechanisms.

Remarkable progress has been made in the theoretical modeling of solar flares, guided by laboratory experiments with such devices as Tokamak, as we heard from Priest and from Spicer. Very impressive simulations of solar flare loop models were carried out by Pallavicini and found to be in good agreement with observations from SMM. Similar simulations may now be used to interpret stellar flare observations from the Einstein satellite.

It is now possible to analyze optical and X-ray data on stellar flares with the help of models developed for the sun, as Giampapa and Haisch have shown. Haisch's detailed examination of the X-ray observations in the framework of the solar loop model was most impressive. It is remarkable how one can derive estimates of such parameters as temperature, density, pressure, loop lengths, magnetic field strengths, etc. The first results show that the loop model is applicable to some but not all types of flares or stars. Kodaira has constructed empirical models of flares which will help to guide further theoretical developments.

Finally, I should like to give my view of what seem to be the major conclusions of the conference:

1) The connection between rotation and magnetic activity seems well established. For the M dwarfs, the depth of the convection zone may be a contributing factor to the magnitude of the X-ray flux.

2) Acoustic waves provide more than enough energy to heat the coronas of M stars, but their heating effect, if any, is probably limited to the chromospheres.

3) Activity on red dwarf stars is remarkably similar to that on the sun, but there are important differences, e.g., stars with $P_{rot} < 7$ days seem to fall in a separate class: they have very large, dark spots and the periods of their cycles are inversely proportional to $P_{rot}$.

4) Starspots last much longer than sunspots and their average fields are much stronger, perhaps by factors of 20-30.

5) Flares on dMe stars are similar on the whole to those on the sun, but the energetics are different. The strongest stellar flares emit perhaps $10^3$ times as much energy as the most energetic solar flares.

Before closing, may I add some comments on the future of research in stellar physics, as a supplement to the excellent presentations by Vaiana and Weiss. We are now clearly on the linear branch of the curve of growth so far as knowledge of red dwarf stars is concerned and it is at this point that we ought to look ahead to the developments that are needed to sustain and accelerate the growth. It seems to me that the key to the future of stellar physics research is high angular resolution, but most of the emphasis in long-range planning, by optical astronomers at least, is on modest increases in the diameters of filled apertures rather than on systems that yield quantum jumps in spatial resolution. While the radio astronomers are planning a very long baseline array with resolution of a few tenths of a millisecond, optical astronomers are looking forward to a resolving power of 0.1 arc sec with the ST and even the proposed New Technology Telescopes can increase the available resolution by factors of 2-3 at most. Such telescopes will be capable of resolving the disks of a few of the brighter red giants, e.g., by speckle interferometry, but only just barely, and the red dwarfs will remain far beyond resolution.

What is needed is a much greater concentration of effort on long base-line optical interferometers, which are now being pioneered for use on the ground by Labeyrie and others, but which must be put in earth orbit for really effective performance. Interferometers with a base-line of 10-15 meters could probably be launched by the space shuttle within a few years, and a base-line of 200 meters, yielding an angular resolution of 0".001 in the visible, should be in reach by the end of the century. That is only 18 years off and I remind you that at least that much time will have elapsed between the start of serious planning for the ST and its actual launch. A gain in optical resolving power by a factor of 100 or more is bound to have an impact on astronomy comparable to that of the large reflecting telescopes that Hale pioneered at the beginning of this century.

DISCUSSION

Linsky: I would like to make a modest comment and suggestion.

Anon: Impossible! (Lots of laughter).

Linsky: Now that I have everybody's attention I will say that a great deal of what has been said at this meeting tells us that we need to monitor objects for long periods of time. The allocation of telescope time, both in space and on the ground, is not usually made by people who recognize that elementary fact. I would like to give a particular example of that. Shortly after Olin Wilson first began his study which led to the

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discovery of activity cycles he applied to the U.S.National Science Foundation for a grant of a small amount of money to continue his work. Even though he was a well-known astronomer and wrote a reasonable proposal the referees said in effect that it was not very exciting science. So it should not be founded. It was only due to the persistence of Wilson himself that he managed to continue and we all know the result. So the moral is that there is a great virtue in long-term monitoring and this should be recognized.

Golub: There is now the possibility of making normal incidence optics in the X-ray region. This raises the possibility, working at 50 Å for instance, of getting down to the diffraction limit, which would give rise to resolution competitive with present radio resolution.

Goldberg: This would be great but it does not remove the need for optical telescopes of the same resolution, of course.

Charles: I would like to refer back to Prof. Vaiana's talk and remind people of an instrument which we hope will become available very soon i.e. EXOSAT. The gratings on board will be very much more sensitive than Einstein's and should extend out to 300 Å. After six months of operation all of the time will be available for guest observers.

Paternò: I would like to make a much more modest comment than Jeff (Linsky) (laughter). It concerns oscillations of these stars. Oscillations are a beatiful tool for determination of the depth of the convective zone, which is in turn ultimately important for the generation of X-rays. For this purpose it is important to detect high-mode p-type oscillations, since it is these which are trapped in the convective zone. It is they which determine the depth of the convective zone since the latter is one of the model parameters which must be fitted to get the best model fit for any observed spectrum. Observationally this is a very difficult task. Incidentally this is the topic of the next meeting in Catania, next June viz. the study of oscillations in order to probe the interior of the stars.

Mullan: I was very glad to hear mention of the South Pole as a site for prolonged observations. At the present time the Bartol Foundation has an observatory there equipped with a 3-inch telescope. You may laugh and ask what astronomy is it possible to do with a 3-inch telescope? Well, solar seismology was revolutionized by that telescope when it was used by Hussak(?), Gregg and Pomeranz. They probed the 5-mins oscillations with a resolution of 1 Hz. The achieved 120 hours of continuous observation of the Sun. We now have an 8-inch telescope giving a 20 cm solar image. This however is just the beginning.

van Leeuwen: (part of question lost) ... you all to observe these stars in open clusters as much as possible in order to constrain the parameters of age and mass. That way I think you can see much more detail in the parameters, in the physics of the stars.

Popper: I have been listening, throughout today's presentations of theoretical interpretations of stellar activity, for some discussion of what appears to me to be one of the primary observational facts calling for theoretical understanding in terms of the spottedness hypothesis. That is the very great amplitudes of phase-related light variations in some active stars. In some cases, modulation over one orbital period of the visual light of the larger, cooler component in a binary may be as great as 30% (e.g. RS CVn, RW UMa). It would seem that a satisfactory theory of stellar activity must show that the amount and distribution of spottedness over the surface, required to account for such large light variation, follows naturally from the theory. I failed to hear any serious reference to this outstanding problem. Four possible explanations occur to me. 1) I didn't listen attentatively. 2) The explanation is so simple and obvious that no comment is needed. 3) The speakers are unaware of the phenomenon. 4) The speakers are aware of it, but have no explanation.