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Summary of the conference

A DEAR COLLEAGUE!

When Cees de Jager asked me a few months ago to present the final Summary of this conference, I hesitated because I feared that it might be very difficult to summarize a meeting where so many topics were discussed. However, Cees told me that he had given many conference-summaries himself and that I did not have to worry because it was relatively easy. It only would require my concentration and attention during the whole meeting. So I agreed. This morning I saw Cees at the coffeebreak. I was tired and sleepy after a long night of struggling through my notes and trying to find a coherent conclusion. I complained to him that I had found the job very difficult and that it had taken me almost all night. To my surprise he fully agreed and said, patting my shoulder and laughing, that it was normal because he himself also usually had great trouble in presenting a summary. So much for a dear colleague!

PROGRESS

What struck me most at this conference was the enormous progress that has been made recently in both theory and observations. Let me briefly mention a few examples. On the observational side I want to recall the observations of Henrichs and his colleagues who detected very accurately the line profile variations in the photospheres and the winds of a few stars in large international campaigns. They found semi-regular variations of a few percent which clearly indicate the influence of rotation and non-radial pulsations on the photosphere and the winds. For the cool stars I want to recall the beautiful work on high spatial and high spectral resolution observations of masers presented by Cohen and Elitzur. These observations clearly show the effects of magnetic fields on the geometrical structure of the shells. Not only the observations but also the theories have made impressive progress. The modelling of mass loss and the effects on the stellar evolution has in some cases reached a remarkable degree of complexity. I want to mention the beautiful work on the pulsation driven winds of Miras by Bowen and the enormous improvements in the theory of model atmospheres of cool stars by Gustafsson. The results of this work and many others can be found in these proceedings.

CHAMPIONS OF VARIABILITY

We have seen at this Colloquium that all luminous stars are "unstable" because they all have variable mass loss. The mass loss rates can be very large, up to about $10^{-3} M_\odot/\mathrm{yr}$, but the variations can also be very large. The most variable hot stars are the Luminous Blue Variables. They vary on all timescales, from weeks to centuries, and suffer large eruptions á la η Car, when as much as about one or two $M_\odot$ can be ejected. The most variable cool stars are the Miras and the R Cor Bor stars. Their mass loss rates can reach values of $10^{-3} M_\odot/\mathrm{yr}$. But the strongest and strangest variations are shown by some F and G supergiants. In this class Var A in M33 and IRC 10420 are the champions. Var A has a strange lightcurve with brightness variations about 3 magn in V in a few months and variations in spectral type from F to M. IRC 10420 shows changes in V of about 1 magn with an erratic lightcurve. It is the hottest OH/IR star with variable OH maser lines and a double peaked Hα profile suggesting mass loss in a disk. Several authors have argued that the irregular variability with sudden drastic changes in all these stars suggests the operations of some non-linear effects. But up to now we do not know what is the cause of these effects and how they are triggered.

MECHANISMS: FROM STEADY MASS LOSS TO VARIABLE MASS LOSS

Radiation pressure on spectral lines is clearly the dominant process for mass loss from hot stars. The calculations by Owocki and colleagues show that the line-driven winds are unstable and that shocks will develop automatically. This explains, at least qualitatively, the X-ray fluxes, the super-ionization and the variable Discrete Narrow Absorption Components. The role of rotation and non-radial pulsations (NRP) of the star in triggering the instabilities and the variability of the winds as not clear. There is observational evidence for rotation modulation of the winds and for profile variations due to NRP but the nature of these effects are not understood. Nor do we know what is the cause of the large irregular variations of the LBVs. Maeder suggested the coupling between the atmosphere close to its Eddington limit and a "geyser"-like instability of the star.

Radiation pressure on dust is clearly important for the acceleration of the winds of cool luminous stars such as Miras and OH/IR stars. However the detailed models by Sedlmaier, Gail and colleagues have shown that dust by itself cannot produce the high mass loss rates of these stars. The reason is that dust will only form at distance from the star where T has dropped to below about 1200 K. But at that distance the density is so low that the resulting mass loss is orders of magnitudes smaller than observed. This problem can be solved by invoking another mechanism to increase the density-scaleheight of the atmosphere. Pulsation and wave-pressure have been suggested in the past. Recently however Elitzur has argued that radiation pressure on molecules, in particular H_2O, might be important for increasing the scaleheight. This effect will be especially efficient if the atmosphere is inhomogeneous. In regions of high density CO can form. This is an efficient cooler so that the atmosphere will quickly develop a two-component structure consisting of hot and cool regions. This "molecular catastrophy", originally proposed for the sun by Ayres, will relieve the problem the dust-formation and it may enhance the dust-driven mass loss rates. Gustafsson has proposed that the molecular catastrophy in M stars is likely due to SiO rather than CO.

Pulsation-driven winds are the most likely explanation for the mass loss from the Mira stars. Bowen presented very impressive ab initio dynamical calculations of pulsation driven winds. His models show the formation of shocks, the reflection and dissipation of waves and several other interesting properties that were not always expected. The models show that immediately behind the strong shocks there is a region that rapidly expands and cools below the equilibrium temperature. These are the likely places of molecule formation which might trigger a molecular catastrophy. Bowen showed that the mass loss is not due to one process, but to the non-linear coupling between pulsation-driven waves, the dissipation and dust formation. These models are very promising in explaining the high mass loss rates on the AGB. In my point of view the major questions that still have to be answered are: what excites the pulsation and what determines the amplitude.

Wave-driven winds for cool stars may be an alternative explanation for the mass loss of cool stars for which pulsation is not important. Hearn presented the results of the first model calculations. I think it is fair to say that these models are still rather crude as the effects of radiation and shocks are not yet included. For instance Cuntz argued that the effects of shock-cannibalism might change the structure of the models drastically. The first models, however, are promising: they produce the right order of magnitude for the mass loss and the velocity *if* the right values of the accoustic flux and of the dissipation length are chosen. The crucial questions however are: what is the origin of the postulated accoustic flux (convection or non radial pulsations?) and how large is this flux. With almost no information about this flux nor about the dissipation length the wave driven wind models enjoy the freedom of two crucial physical parameters that can be adjusted as desired.

Wave pressure may be important for the explanation of the high mass loss rates of F and G supergiants. These stars are too cool for a dominant role of radiation pressure, and too hot for pulsation driven winds with radiation pressure on dust. De Jager has shown that the F and G supergiants have large "turbulent" velocities in their photospheres. If these observed velocities reflect the presence of gravity waves and pressure waves with large amplitudes, then the wave-pressure together with radiation pressure will reduce the effective gravity in the atmospheres drastically. This may result in the high mass loss rates of the most luminous F and G supergiants. I think that the coupling between the results of the spectral studies to determine the field of motions in the atmospheres and the wave-driven wind models might be fruitful.

WHAT CAUSES THE LARGE VARIABILITY?

The mechanisms described above may be able to explain the high mass loss rates and the wind velocities but it is not clear how to explain the large *variabil-*

ity for which so much evidence was reported at this Colloquium by e.g. Cohen, Elitzur, Feast, Henrichs, Humphreys, Smolinski, Stahl and van Genderen. In fact most of the observed variations, such as the ejection of shells or blobs in almost all luminous stars and the changes in spectral type of the LBVs and of the strongly variable F and G supergiants, cannot be explained at all by the (quasi-)stationary mass loss models. They seem to require a drastic variability of the underlying star.

The only suggestion at this conference about the possible nature of the required stellar instability was made by Maeder. He showed that luminous stars with $T_{\rm eff}$ near 8000 to 10 000 K may have a density inversion below the photosphere due to the high radiation pressure. This density inversion will produce a dynamical instability of the outer layers which in turn will result in a high mass loss rate. As mass is ejected at a high rate, the density inversion will move inwards resulting in a continuing high mass loss. (This mechanism is very similar to that of a geyser. In a geyser the boiling-point moves downward as the pressure is reduced by water-ejection. In a star the ionization-point moves downward as the pressure is reduced by mass-ejection). This high mass loss will stop when the Kelvin-Helmholtz time of the layers above the instability becomes equal to the ejection time. The calculations by Maeder show that a star of 60 $M_\odot$ may eject as much as 0.1 $M_\odot$ in a few decades.

It is clear that such eruptions will produce large spectral variations and possibly also result in sudden dust formation. These predicted eruptions show some resemblence to the observed outbursts of the LBVs. However these usually occur at $T_{\rm eff} \simeq 15000$ to 20 000 K which is hotter than predicted by Maeder. It is also possible that the large variations of some F and G supergiants are produced by such a mechanism.

My personal feeling is that the most luminous stars are all very close to their Eddington limit, either by radiation pressure alone (the hotter stars of $T_{\rm eff} \gtrsim 12000$ K) or by a combination of radiation pressure and turbulent or wave pressure. Whenever a star is close to its Eddington limit, its effective gravity in the photosphere will be so small that a small disturbance in the underlying layers may result in large mass ejection and strong variability. We still have to find the cause of this disturbance, but we may not have to look for drastic effects.

An example of such a small effect that has significant consequences has been given by Pauldrach and Puls (1991, Astr. Ap) who showed that a minor increase of the radius of P Cygni by only 1.5 per cent increases the radiation driven mass loss rate by almost a factor three and reduces the wind velocity by a factor 0.3 !

TWO QUESTIONS

(a) Why do we find evidence for disks around so many luminous stars? The observations of IRC 10420 show that the Hα line often has a double- peaked emission. Moreover, the optical spectrum is polarized. These two effects clearly suggest the presence of a disk around the star (Humphreys). The SN 1987a also shows evidence that the red supergiant wind was non- spherical. The interaction of the blue supergiant wind with the previous red supergiant wind produces a ring, rather than a shell. This can only be explained by assuming that the red supergiant wind was highly non-spherical (Feast). Other examples of non-spherical mass loss from high luminosity stars are the B[e]-supergiants whose Balmer profiles clearly indicate that the high mass loss occurs predominantly in the equatorial plane.

It is obvious that in all these cases rotation plays a crucial role. However, a simple estimate shows that the reduction of the effective gravity at the equator is insufficient in itself to explain why the mass loss is so strongly concentrated in the equatorial regions, unless the stars would rotate at $\gtrsim 0.8$ times the break-up velocity. So this suggests that the disks are due to a coupling of the rotation with some other mechanism(s). We do not really understand these other mechanisms nor their coupling with the rotation. The expected enhancement of the amplitude of non-radial pulsations along the equator due to rotation is only one of the possible mechanisms. For the hot luminous stars the bi-stability mechanism of radiation driven winds may be efficient in producing disks (Lamers and Pauldrach, 1991 Astr. Ap.). I think that it is worthwhile to investigate other possible causes of disk-formation in luminous stars, especially for the cooler ones.

In this context we should not forget that a substantial fraction of the very luminous stars may be in binaries with unseen companions.

(b) What happens when a star evolves onto its Eddington limit? The classical Eddington limit was defined as the position in the HR diagram where the gravity of the stars is equal to the force produced by the radiation pressure in the photosphere *by electron scattering.* This results in a horizontal limit in the HR diagram for stars with a single mass-luminosity relation. However, during the last decade it became evident that the real Eddington limit for massive stars is not a horizontal line in the HRD but that it is a dip in the HRD with the deepest point around $T_{\rm eff} \simeq 9000$ K. This is due to the fact that radiation pressure in the photosphere is largest near 9000 K where the atomic opacity reaches a maximum (see e.g. Lamers and Fitzpatrick, 1988 Ap.J., and Gustafsson these proceedings). Moreover, the reduction of the mass of a star due to its mass-loss results in a continuously lowering Eddington limit for that star.

The result of both effects is that luminous stars (and also less luminous stars with a high L/M ratio) run the risk of hitting their Eddington limit during their evolution. Standard model-atmosphere theories predict that the atmospheres of these stars will be "bloated" due to their low or almost vanishing effective gravity. This would results in a high mass loss rate with low velocity. However observations suggest that the stars may become unstable and suffer mass loss hiccups. Maeder has suggested that the high variable mass loss of LBVs may be due to their close approach to the Eddington-limit. He has argued that the LBVs may be stars that evolve onto their Eddington limit from the left in the HRD. When they eject a substantial amount of mass ($\simeq 0.1$ to $1 M_\odot$) during a large eruption, they will move back to the left in the HRD. They may then move to the right again and reach the Eddington limit several times. This situation is sketched in Fig. 1a.

However, what happens when a star hits its Eddington limit from the right of the HRD? This situation is likely to occur for star with $L \simeq 3\,10^5 L_\odot$, because they may safely evolve from blue to red supergiants just passing under the Eddington-dip. However, when they have lost a substantial amount of mass and evolve to the left in the HRD their L/M-ratio will be larger than before so their Eddington limit (with its dip near 9000 K) will be lower. (Fig. 1b). Will they also suffer large outbursts? If so, these outbursts may be very different from those suffered by the LBVs because the opacity and hence the effective gravity will change completely differently in the $T_{\rm eff}$-regime above 9000 K where the opacity *increases* with decreasing temperature and below 9000 K where the opacity *decreases* with decreasing temperature. If the stars which move onto their Eddington limit from the right also suffer large outbursts, will they move back to the right of the limit or will they cross the Eddington-dip? The answer to these questions may solve the puzzle of the highly variable F and G supergiants, such as ρ Cas or Var A in M33, which show large variations in spectral type in decades.

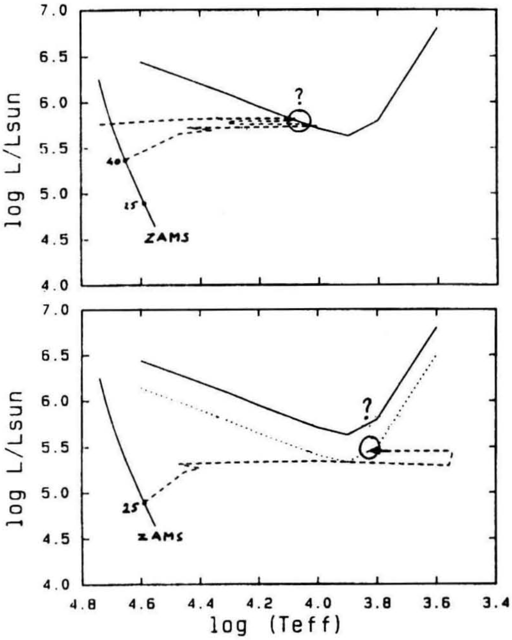

Figure 1: A schematic picture of evolution tracks hitting the Eddington limit. The Eddington limit is shown by a full line. It reaches its lowest point in the HRD near $T_{\rm eff} \simeq 9000$ K where the photospheric flux-mean opacity is largest. The upper figure shows a track of a star of $40 M_\odot$ which runs into its Eddington limit at $T_{\rm eff} \simeq 12000$ K. The star may suffer repeated outbursts. This might explain the outbursts of the Luminous Blue Variables. The lower figure shows two Eddington limits. The upper one is for the L/M ratio of a $25 M_\odot$ star after the main-sequence phase. The track can pass under this Eddington limit. The lower dotted curve is the Eddington limit for the same star after its red giant phase when it has lost a substantial fraction of its mass. The track runs into its Eddington limit from the right near $T_{\rm eff} \simeq 6000$ K. Maybe this can explain the outbursts of the variable F and G hypergiants such as IRC 10420.

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