CONCLUDING REMARKS

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In conclusion of our conference, the last duty which I am being called upon to perform is to summarize what we have heard in the last few days, to outline the present state of the subjects under discussion, and to single out the most important ones deserving further attention in the future. To do so is obviously not easy; for so much has been brought up in the past few days that any kind of more detailed summary would exceed the time available for these remarks. Nevertheless, in what follows I shall attempt to do so by subjects discussed in the past sessions - in the hope that this overview may stimulate our thinking in the future.

Before doing so I should, however, like to comment on a topic not specifically discussed in any one single session, but which overshadowed them all; namely, an unprecendented impact of new observational data forthcoming in recent years from the telescopes operating in space. While the study of wide binaries (at least its astrometric aspects) may have to await the consumation of the European project Hipparcos to experience such an impact, at least half of all new data presented at this colloquium on close binary systems have been based on observations obtained by use of the International Ultraviolet Explorer. And when, in the latter part of the present decade, the existing facilities will be augmented by the U.S. Large Orbiting Telescope, the influx of new and unique data will become simply overwhelming.

Are we sufficiently well prepared to cope with their output; or are we at least taking the necessary steps to put us in this position? Even at the present time (as we have witnessed, in particular, in the 3rd session of our colloquium), their examination has been more qualitative than quantitative; for to exhaust all information implied in these new data would claim more time - and greater scientific manpower - than is available so far. Is this increased manpower "in the pipelines" to be ready when they are needed? It is a sad comment on the contemporary situation in our field that - if anything - the opposit is the case; and that while we still continue to spend tens or hundreds of millions of dollars (or marks) on the design, construction and launch of space

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vehicles for which astronomical requirements are used as a pretect of the injustification, no adequate steps are being planned to train scientific manpower needed to cope with their output - with the disturbing prospect that a large part of the new data being obtained in space may gather but dust on the Earth; or receive only a cursory attention. If so, posterity would no doubt condemn us severely for this lack of foresight in planning for the future; and will wonder why we were so much better at hardware engineering than human education - is there still time to bring them both to closer harmony?

But to return from future prospects to the present, and from space back to the ground: what did we learn at this colloquium about the major problems, some of which were mentioned in my introductory remarks? The main one of these - concerning the "evolutionary paradox" met so frequently among certain types of binary systems - is still very much with us; and I dare say in an even more disturbing manner. The principal evidence aggravating the situation has been provided (and keeps forthcoming) from wide binary systems, the properties of which were under discussion in Session II.

From all data we possess today (and for their fuller survey cf. Agayev, Guseinov and Novruzova, 1982) it transpires that the evolutionary paradox - which stares us in the face in visual binary systems like Sirius or Procyon - is replicated in too many other to regard these latter stars as exceptions to the rule. The above-mentioned catalogue of white dwarfs by Agayev et al discloses that, among almost 500 such objects, 62 (or 13%), including Sirius and Procyon, are components of wide binary systems; and, in view of the small absolute brightness of such objects (i.e., with observational selection hampering their discovery), the actual percentage of binary systems with white dwarf components attending Main Sequence stars is probably much higher. Such pairs are, therefore, by no means unusual or exceptional phenomena; and to account for their existence has become an important astrophysical problem.

In considering the implications of this problem which I raised already many years ago (cf. Kopal, 1959; pp. 542-543), let us adhere to the view that white-dwarf (or, generally, more evolved) components of such systems had once to be more massive of the two, and lost excess mass at subsequent stages of their evolution. If any of these stars were initially more massive than 2-3 ⊙ - and many of these must have been if they belonged to Population I or disc-type population - they must have got rid of excess mass to suppress the remainder below the Chandrasekhar limit as a condition sine qua non for them to be able to become degenerate.

Some investigators (e.g., Lauterborn, 1970) considered a possibility that the excess mass may have "overflown" on to their mates; but conditions necessary for this to happen are so extremely specialized as to make them scarcely of astrophysical interest. In order to demonstrate this, it is sufficient to recall that the velocity of escape from the gravitational field of a star is as a rule 10-100 times higher than those necessary for the zero-velocity surfaces surrounding the binary system (regarded as a rotating gravitational dipole) to remain closed. For instance, in the case of Sirius, the mass of the A0-component is equal to 2.3 ⊙; and its radius, 1.76 ⊙; while those of its attendant white dwarf are 0.98 ⊙ and 0.022, respectively. The relative orbit of the two stars is markedly eccentric (e = 0.59); and its semi-axis A = 7.62 astronomical units. As a result, at the mean distance of both components, the fractional radius of the A0 star is only 0.0011; and its angular diameter, as seen from the secondary component, 7.5 arc minutes. The velocity of escape from the gravitational field of Sirius A is in excess of 700 km/sec; and although it may have been less for the present Sirius B at the peak of its post-Main Sequence expansion, it is by almost two orders of magnitude higher than that necessary to make the surface of zero velocity closed around the systems as a whole. As a result, no dynamical necessity exists for ejected matter to wander within the system until captured by the companion star. It can escape the system altogether,and this is what it probably did in this (and other similar) case.

But Sirius - while a typical example of the "evolutionary paradox" - much more conspicuous than Algol or U Sagittae - is still not the worst objection to the conventional interpretation of this paradox. At least in Sirius (or Procyon) the present white-dwarf component proves to be the less massive of the two. But - still within our neighbourhood in space - in the visual systems of o^2 Eridani ($m_{1,2}$ = 0.42 ⊙ + 0.20 ⊙) or Stein 2051 ($m_{1,2}$ = 0.48 ⊙ + 0.22 ⊙) the white-dwarf components are more massive of the two; and if the entire mass of the present secondaries were transferred on to their white-dwarf primaries, their total masses would still be too small for reaching the white-dwarf stage during the entire age of our Galaxy! Or consider the quadruple system of Giclas 107-69 and 70, consisting of two red and two white dwarfs of total mass not exceeding that of our Sun.

Moreover, it is not only in wide binary systems that we encounter white dwarfs among their components; but in close (spectroscopic) binaries as well. Consider, for instance, the close pair V 471 Tauri (discovered in 1970 by Nelson and Young), with an orbital period of only 0.5212 days, which (on account of a chance direction from which we see it) happens to be also an eclipsing variable. It consists of two components of combined mass equal to approximately 1.4 ⊙ (cf. Yound and Lanning, 1975), one of which is a K0 V dwarf on (or still contracting towards) the Main Sequence, and the other a white dwarf; separated from each other by less than three solar radii. Their masses are nearly equal (cf. Young and Lanning, op. cit), but the dimensions are not; and an ingress (or egress) of the eclipse of the white dwarf by its Main Sequence mate lasts only about 40 seconds!

The particular significance of this system rests on the fact that not only are its component stars of manifestly the same age, but that also the absolute value of this age is known. As (by its proper motion)

V 471 Tauri is a member of the Hyades cluster, the system - in common with all other stars of this cluster - cannot be much older than 600 million years (i.e., the time which elapsed since the commencement of the Paleozoic era on the Earth). During this time our Sun - a much older star - managed to burn only a few per cent of its internal hydrogen supply; yet V 471 Tauri - a system whose combined mass amounts at present to 1.4 ⊙ - evolved far enough for one of its components to become a white dwarf! Obviously the mass of its progenitor must once have been much larger than it is today - but its excess was not merely transferred on to its mate (whose present mass is too small even today to have served for such a receptacle), but must have escaped the system altogether - as it almost certainly did in the case of Sirius and Procyon.

It should be emphasized that the real cause of mass ejection in more advanced evolutionary stages of the stars is intrinsic to the star itself; and its onset is to be sought in its own internal structure; it does occur even if the star is single (stellar winds!); and whenever direct observational evidence is on hand to disclose the actual velocity of escape (such as furnished by spectroscopic observations of giants, Wolf-Rayet stars, or of the Novae), it proves to range from several hundred to a few thousand kms per second. Matter escaping with such speeds would pay but scant attention to the presence of any companion in binary systems - especially in wide binaries where companion stars become but little more than passive onlookers of dramatic phenomena which produce the mass loss.

But even in close binaries, in which post-Main Sequence expansion of the components can bring stellar surfaces to actual contact with their static Roche limits (which can never happen in wide binaries of the Sirius-Procyon type!), such a phenomenon can at best facilitate mass escape (by reducing gravity in the neighbourhood of the inner Lagrangian point), or render the loss non-isotropic; but cannot by itself cause it. In close binaries of the Algol -U Sge (or U Cep-type) some of the escaping matter may be detained by hydrodynamical reasons to linger in the system for some time, and give rise to spectroscopic phenomena observed in many such systems. But that the bulk of it - and it may be from one-half to nine-tenths of the original mass of the star - is ejected from the gravitational field of the systems seems to be its likeliest fate; at least it offers the simplest hypothesis which can be brought in harmony with all observed facts; and none are known to be contrary to it.

More detailed aspects of this situation have already been discussed by the present speaker on pp. 415-430 or 472 of his Dynamics of Close Binary Systems (Kopal, 1978), and need not be repeated in this place - beyond stressing again that a postulate of more complicated processes - such as low-velocity mutual transfer of significant fraction of stellar masses between the components - is not only physically unlikely, but unnecessary; for the observed facts can be just as well reconciled with a physically simpler (and observationally better-founded)

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process of high-velocity mass escape by stellar winds. To insist - in the fact of such a situation - on low-velocity mass transfers (or exchange) between the components provides, to my mind, a good example of "Procrustean Science", in which by chopping off, (or turning our backs to) various phenomena, or accumulating superfluous hypotheses, we not only strive to fit the observed picture on to the Bed of Procrustes of our preconceived opinions, but also offend the spirit of "Occam's razor" requiring that "entia non sunt multiplicanda praeter necessitatem".

However, even if we are willing to dispense with unncessary hypoteses which may obstruct our way towards fuller understanding of the observed facts provided by binary systems, this still does not mean that we are out of the woods. That stars, at certain stages of their post-Main Sequence evolution, are likely to divest themselves of 50% - 90% of their original mass appears to be attested by evidence provided by binary stars almost without doubt; and that the bulk of this loss occurs at high speed is very probable; but the specific source of energy necessary to bring it about is still obscure; though the demands on it are considerable.

To demonstrate this on a specific example, consider the well-known semi-detached binary system of Algol, whose principal (Main-Sequence) component of spectral type B8 possesses a mass close to 3.8 ʘ, while that of its evolved component of spectrum gKO IV is only 0.82 ʘ (Tomkin and Lambert, 1978). If (to account for its present evolutionary stage) Algol B originally possessed a mass close to (say) 5 ʘ - i.e., was more massive than the present Algol A - a removal of some 80% of its original mass from its present size of 3.4 solar radii to infinity would have called for an expenditure of energy of the order of

$$\frac{3}{2} G \frac{(4.2\ m_{\odot})^2}{3.4\ R_{\odot}} = 3.5 \times 10^{49} \text{ ergs}$$

($G=6.67\times10^{-8}$ $cm^3/g\ sec^2$ representing the gravitation constant), equal to the present nuclear energy output of 2.4×10^{34} ergs/sec of that star for some 50 million years - a tall requirement, but not inconceivably so; and our main task (as yet unfulfilled) remains to identify its mechanism of release.

But this is not the only task challenging the students of stellar evolution; for observations continue to dangle before us a series of other facts which we cannot yet explain; and these concern mainly the distribution of double stars in time. As is well known, binary systems (of all separations) constitute at least 70-80% of stellar population in the neighborhood of the Sun; and from their various characteristics we infer that most of the latter belong to Population I stars, younger than 10^9 years (i.e., about one-tenth of the age of our Galaxy). But we mentioned already that, on dynamical grounds, such binary pairs - not only close (i.e., spectroscopic or photometric), but

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also wide (i.e., visual or astrometric) - are virtually undissolvable for time intervals of the order of 10^{10} years. And this, in turn, is bound to give rise to the question: where are those older than 10^9 years - where are the binaries of the disk-type population contemporary with our Sun?

And the inquiry becomes all the more perplexing to us when we turn to the old stars of Population II: where are the binaries (photometric, to be sure; for no other could be discovered) in the globular star clusters? Eclipsing variables of W UMa-type (about which more will be said later on) could be as easily discovered in globular clusters as short-period cepheids (especially of Bailey's c-type). Sawyer's 1975 Catalogue of 1421 Variable Stars in Globular Star Clusters lists only 3 eclipsing variables in 3 different clusters (NGC 3201, 5139 and 6338) which, however, are probably all foreground stars. Attempts made (e.g., by Batten, 1973) to explain away this disparity by evolutionary effects, which could render ageing binaries more immune to observational detection, are unconvincing. No; most probably the disparity is real, but its cause remains so far obscure.

And the same is true of the conspicuous disparity in the frequency of occurrence of close binaries among absolutely brightest stars of young Population I in our Milky Way system and in the neighbouring spiral galaxies - such as the Andromeda and Triangulum nebulae; or (to a lesser extent) in the Magellanic clouds. What is the cause of this behaviour? Is it a different type of interstellar substrate, or of interstellar magnetic fields? We do not yet know; and as long as this is the case, we cannot but acknowledge the fact that, in following the tracks of nuclear evolution of the binary stars of constant mass, somewhere in the latter parts of the post-Main Sequence stage we have probably lost the way.

And if this is true of evolved components of binary systems at the time of their principal mass loss, it is equally true to say that as regards the second and, in many respects, even more enigmatic group of predominantly dwarf objects much discussed in Session III of our Colloquium and usually classified as close binaries of W Ursae Maioris type - stars exhibiting well-nigh continuous variation of light, suggestive of the fact that these systems - if binary - consist of components which are in virtual contact (or even surrounded by a common envelope). Although the W UMa-stars have been the subject of more communications presented in Session III than any other group of close binaries, no two investigators agree about models which could account for all aspects of the observational evidence - a fact from which we can only conclude that we are still some distance from a fuller understanding of their real nature.

There are several reasons for this situation which deserve special attention. First, the extraordinary abundance of the W UMa-type stars in space. Already more than thirty years ago Shapley (1948) pointed

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out that these are 20-30 times as numerous in the sky as all other types of eclipsing variables lumped together - an astonishingly high frequency, confirmed subsequently by Kraft (1965) or Eggen (1967) who concluded that one out of 1000 - 2000 stars of the same spectral class is a variable star of W UMa-type, corresponding to about two such binaries per million cubic parsecs. One of them - i Boo, at a distance of 12.6 parsecs - belongs, in fact, among the nearest stars; with VW Cep only 18.9 parsecs away, being the second nearest W UMa-type star to us in space.

Secondly, the frequently encountered instabilities of their light - and velocity changes, variations of periods, etc., strongly suggest that W UMa-stars constitute secularly unstable configurations evolving on the Kelvin time-scale, with lifetimes of the order of 10^7 years. If so, however, the total number of stars in the Galaxy which may have passed through the W UMa-stage at one time or another may be 10^2 - 10^3 times higher than the number of those we see now in the act - possibly as high as one such star per 10^5 cubic parsecs (which corresponds to about one star in 10^4 in our neighborhood).

Third, known stars of the W UMa-type are found to cluster (albeit rather loosely) around the Main Sequence, and are, therefore, presumably hydrogen-burning objects. They are, moreover, found anywhere along the Main Sequence - from B-type stars (such as EM Cep or V 701 Sco) to those of late K dwarfs; the majority belonging to spectral classes F and G of luminosity Class V. These facts, perhaps, do not deserve undue emphasis; for the fact that only few W UMa-type objects are known to be of early spectral classes may be due to the rapidity of their evolution; and the paucity of K or M stars among them may again be due to observational selection (i.e., low intrinsic luminosity of such objects).

Fourth, quite a number of W UMa-type systems prove to be components of wide binaries - such as i Boo (=ADS 9494B), AK Her (=ADS 10498A); or constitute common proper-motion pairs (such as VW Cep with HD 199476, or W UMa itself with BD +55°1351). Of greater importance is, however, the fact that many occur also in star clusters of known age. None was, to be sure, found in any globular cluster so far; but many galactic (open) clusters are known to contain them in considerable numbers.

To give some examples, the southern cluster IC 2994 which provides the celestial home for BH and LW Cen (Eggen, 1967) is so young that its stars of spectral class later than B3 are still contracting to the Main Sequence (cf. Thackeray, 1964); so that the variables just quoted cannot be older than 10^7 years. TX Cnc in the Praesepe cluster cannot, on the other hand, be younger than 6-8 x 10^8 years (which is the age of that cluster); while variables like EP to ES Cep (cf. Efremov et al., 1964; Hoffmeister, 1964; or Kurochkin, 1965) in an old galactic cluster NGC 188 must be at least 5 x 10^9 years old (Eggen and Sandage, 1969; or Demarque, 1979). The W UMa stars in our neighbourhood - judging from their kinematic characteristics (cf. Schatzman and Rigal, 1954;

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Rigal, 1955; Artiukhina, 1964; or Popov, 1964) - appear again to belong to the disc-type population of the Galaxy, of age comparable with that of our Sun.

All these facts taken together rule out certain avenues of approach to the interpretation of observed phenomena exhibited by W UMa-type stars, and weaken others. They virtually eliminate (cf., e.g., Van't Veer, 1980) a possibility that such stars constitute contact configurations, in which both components of a detached close binary expanded towards their Roche limits as a result of incipient hydrogen shortage. For quite apart from the fact that these stars continue to cluster around the Main Sequence (and are, in particular, no subgiants) some such binaries which can be dated by the cluster to which they belong, could not have reached the state of hydrogen exhaustion since their birth, on account of their small mass. Consider, for instance, the star TX Cnc which - as a member of the Praesepe cluster - cannot be older than some 600 - 800 million years. The combined mass of this star (deduced from spectroscopic observations) is close to 1.9 ☉, which (if divided between the two components) is not large enough to compel them to emark on post-Main Sequence expansion since the time when our Sun - a star of comparable mass - was at the commencement of the Paleozoic era; with long future still ahead of it on the Main Sequence. It has been pointed out at this colloquium by Dr. Van't Veer that not all stars of any given cluster need to be of the same age; but surely none can be older than the cluster itself!

But quite apart from problems arising in this connection, the observed facts pointed out earlier give rise to the following question whose importance overshadows all others - and one which becomes the Skylla and Charybdis for all theories on the evolutionary significance of variable stars of the W UMa-type. With so many such stars filling the sky (especially if the variable phase represents only a transient stage of their evolution) where are the progenitors of these objects, or descendants of those which may already have passed through their variable stage in the past? Those which we observe today cannot, in particular, have descended from any other know type of variable stars - for any such hypothetical parents would be by orders of magnitude too few for their offspring! In fact, the only way to avoid this embarrassing predicament - and which would seem to be able to provide ample reservoir for ancestry as well as of the descendants - would be to put forward a tentative hypothesis that the present W UMa-type variables are really single stars, which can temporarily stimulate close binaries in all manifestations which this may entail; and eventually return to the stage at which they will shine again with constant light, and thus cease to attract attention.

Let us develop what we mean in a few more words. Suppose, for the sake of argument, that the W UMa-stage of variability of the respective star is preceded by a contraction (rather than expansion to the Roche limit) on the Kelvin time-scale - fast enough for the angular momentum of axial rotation to be conserved in its course.

This would, in turn, be bound to increase the angular velocity of axial rotation - possibly beyond the stage at which the initially spheroidal configuration will acquire three-axial form. Theory of stellar rotation can neither prove, nor deny, such a possibility so far. But once such a configuration has attained the form of a pear-shaped figure, it would become a variable star; and, moreover, photometric as well as spectroscopic observations at a distance could scarcely distinguish phenomena exhibited by a rotating dumb-bell figure from those produced by a contact pair.

While the surface manifestations of these alternative models could, we repeat, be very much the same, dynamically their difference would be profound. For whereas a binary star (close or wide) represents a dynamical system formed by an irreversible process - and the components of which possess two independent centres of gravity - a rotating dumb-bell figure possesses only one centre of gravity; and could, therefore, revert to a less extreme form by despinning. If, moreover, such a configuration can be de-spun below the limit at which it will return to spheroidal form, its light would cease to be variable; and the object would lose its identity as a W UMa-type star. The requisite de-spinning could, in turn, be brought about if (as is likely) the dumb-bell configuration did not rotate as a rigid body. For if so, a gradual dissipation of kinetic energy of axial roation into heat through viscous friction could lessen the spin and help the configuration to revert to spheroidal star shining once more with constant light; with only a diminished store of potential energy to draw upon in the future.

The foregoing "scenario" remains, of course, still wholly hypothetical - though not any less likely than many others which have been put forward in recent years to explain the characteristics of W UMa-type stars - and may deserve further consideration. However, its more detailed elaboration must be left to a more courageous individual, with more years ahead of him than may be vouchsafed to your present speaker. Observations alone are, alas, not likely to provide a more direct answer to our inquiry in the foreseeable future. For consider again the variable star i Bootis, which is the nearest W UMa-type star to us in space. At a distance indicated by its trigonometric parallax of $0''.079 \pm 0.005$, its apparent angular diameter should be no greater than $0''.001$ - i.e., still at least an order of magnitude below the limit at which we could begin to discern its shape by speckle interferometry or any other method of direct observation; and this situation may not change at least for many years to come.

And at this not too optimistic note, the time has come for me to stop and bidd all future investigators of these problems God speed. If, in my opening remarks, I ventured to quote some words of Friedrich Schiller from his Ode an die Freude, now I am almost tempted to take issue with his optimism, reflected in his words (echoed from the same source), "Brüder, überm Sternenzelt muss ein lieber Vater wohnen". Sometimes, in wrestling with our problems concerning double stars

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(and not these alone) we may ask ourselves, in the midst of our perplexities, why did the good Father have to make things so difficult for us to read His work with fuller understanding? Maybe, He has done so only to test our mettle; and if so, we should not fail to meet the challenge and persevere in our efforts to unravel the celestial wonders (at least in so far as they concern the topic of our present colloquium) until all basic problems exercising us at present will be solved - and the way open to other problems, of which we may as yet have no inkling, and which will test the mettle of our descendants. And, in the meantime,..."Froh, wie seine Sonnen fliegen, durch des Himmels prächt'gen Plan; Wandelt, Brüder, eure Bahn, freudig wie ein Held zum Siegen".

REFERENCES

Agayev, A.G., Guseinov, O.H. and Novruzova, H.I.: 1982, Astrophys. Space Sci., 81, 5.
Artiukhina, N.M.: 1964, Per. Zvjozdy, 15, 127.
Batten, A.H.: 1963, in Binary and Multiple Star Systems, Pergamon Press, London.
Demarque, P.: 1979, in IAU Sympos., No. 85; p. 281.
Efremov, Y.N., Kholopov, P.N., Kukarkin, B.V. and Sharov, A.S.: 1964, Inf. Bull. Var. Stars, No. 76.
Eggen, O.J.: 1967, Mem. Roy. Astr. Soc., 70, 111.
Eggen, O.J. and Sandage, A.: 1969, Astrophys. J., 158, 669.
Hoffmeister, C.: 1964, Inf. Bull. Var. Stars, No. 67.
Kopal, Z.: 1959, Close Binary Systems, Chapman-Hall and John Wiley London and New York.
Kopal, Z.: 1978, Dynamics of Close Binary Systems, D. Reidel Publ. Co. Dordrecht and Boston.
Kraft, R.P.: 1965, Astrophys. J., 142, 681, 1588.
Kurochkin, N.E.: 1965, Inf. Bull. Var. Stars, No. 79.
Lauterborn, D.: 1970, in Proc. IAU Colloq. No. 6, Copenhagen; pp. 190-192.
Nelson, B. and Young, A.: 1970, Publ. Astr. Soc. Pacific, 82, 699.
Popov, M.V.: 1964, Per Zvjozdy, 15, 115.
Rigal, J.L.: 1955, C.R. Acad. Paris, 240, 50.
Sawyer, H.H.: 1975, David Dunlap Obs. Publ., 3, No. 6
Schatzman, E. and Rigal, J.L.: 1954, C.R. Acad. Paris, 238, 2392.
Shapley, H.: 1948, in Harvard Centennial Symposia (Harv. Obs. Mono. No. 7), pp. 249-260.
Thackeray, A.D.: 1964, in "The Galaxy and Magellanic Clouds", IAU-URSI Sympos., No. 20, pp. 18-22.
Tomkin, J. and Lambert, D.L.: 1978, Astrophys. J., 222, L119.
Van't Veer, F.: 1980, Acta Astron., 30, 381.
Young, A. and Lanning, H.H.: 1975, Publ. Astron. Soc. Pacific, 87, 461.

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