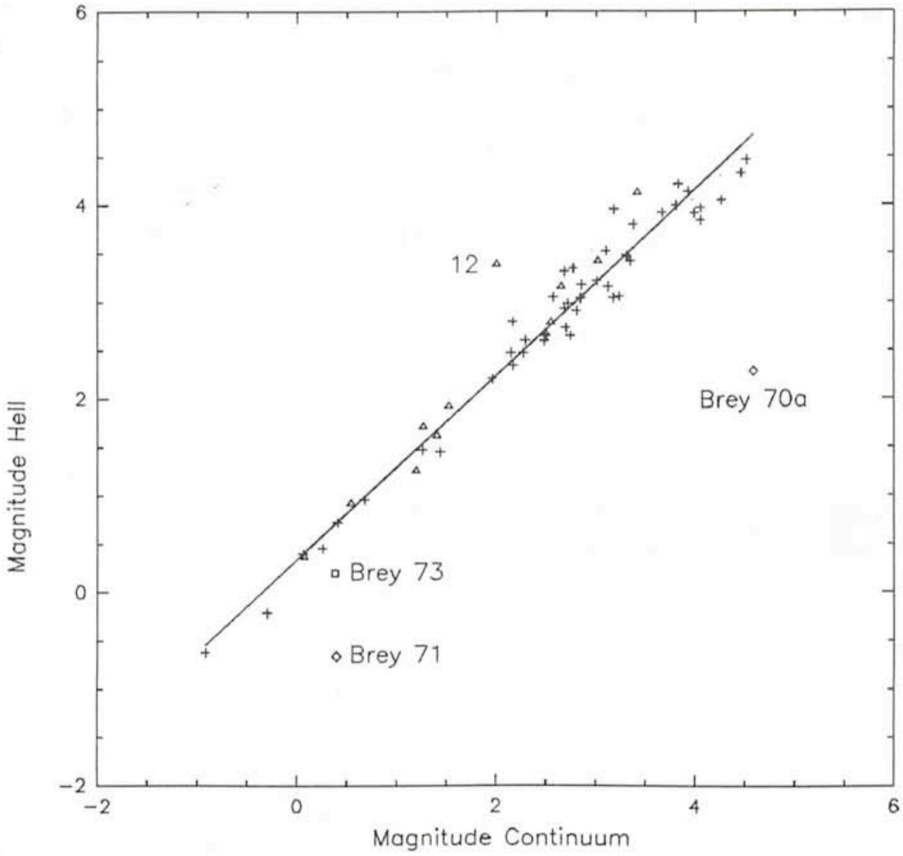

Figure 6: *Plot of the He II relative magnitudes versus the continuum magnitudes of all stars of the frame (90 arcsec × 140 arcsec). The known W-R stars Brey 70a, Brey 71 and the Brey 73 association show a conspicuous He II brightness excess. The stars belonging to the aggregate are represented by triangles. Most of the stars follow a close relationship* v (λ 4686 Å) = 0.96 v (λ 4794 Å) + 0.34 and with a σ rms of 0.22 magnitude after elimination of Brey 70a, Brey 71 and Brey 73. Star 12 is a faint star of the cluster, probably a red one which would need deep, good seeing B and V photometry.

Cowley, A.J., Hutchings, I.B.: 1979, *P.A.S.P.* **90,** 636.

Debray, B., Dubout, R., Llebaria, A., Petit, M.: 1988, *Astron. Astrophys.* (submitted).

Feitzinger, J.V., Schlosser, W., Schmidt-Kaler, Th., Winkler, C.: 1980, *Astron. Astrophys.* **84,** 50.

Feitzinger, J.V., Isserstedt, J.: 1983, *Astron. Astrophys. Supp. Ser.,* **51,** 505.

Henize, K.G.: 1956, *Astrophys. J. Suppl.* **2,** 315.

Heydari-Malayeri, M., Magain, P., Remy, M.: 1988, *Astron. Astrophys.* **201,** L 41.

Lortet, M.C., Heydari-Malayeri, M., Testor, G.: 1986, in *Luminous stars and associations in galaxies,* Proceed. IAU Symp. **116,** 401.

Lucke, P.B.: 1972, Ph.D. Thesis, University of Washington.

Lundström, I., Stenholm, B.: 1984, *Astron. Astrophys. Suppl.* **58,** 163.

Morgan, D.H., Good, A.R.: 1987, *MNRAS.* **224,** 435.

Prévot-Burnichon, M.L., Prevot, L., Rebeirot, E., Rousseau, J., Martin, N.: 1981, *Astron. Astrophys.* **103,** 83.

Smith, L.F.: 1968, *MNRAS.* **140,** 409.

Stetson, P.B.: 1987, *P.A.S.P.* **99,** 191.

Van der Hucht, K.A., Hidayat, B., Gunowan Admiranto, A., Supelli, K.R., Doom, C.: 1988 Preprint.

Walborn, N.R.: 1977, *Astrophys. J.* **215,** 53.

Walborn, N.R.: 1980 (Private communication).

Weigelt, G., Baier, G.: 1985, *Astron. Astrophys.* **150,** L 18.

Westerlund, B.E.: 1974, Proceedings of the first European Astronomical meeting in Athen, September 4–9, 1972, Volume 3. Springer, Berlin, Heldeberg, New York, p. 39.

Spectroscopic Identification of White Dwarfs in Galactic Clusters

D. REIMERS, Hamburger Sternwarte, Universität Hamburg, F.R. Germany
D. KOESTER, Department of Physics and Astronomy, Louisiana State University, USA*

The End Products of Stellar Evolution

The end products of the evolution of single stars are well known: low mass stars leave white dwarf remnants, massive stars undergo a supernova explosion with either a neutron star or a black hole as a remnant.

In a first approximation, it appears to be only the initial mass which determines whether a star ends its life peacefully as a white dwarf or undergoes a core collapse with a quasi instantaneous energy release of $\sim 10^{53}$ erg, visible as a supernova explosion.

Estimates of the maximum initial mass limit M_{WD} for formation of white dwarfs have been made by various techniques.

One possibility is to compare the supernova type II rate with the birth rate of massive stars in our galaxy. Since the former rate is extremely uncertain and can be observed only in external galaxies whereas the initial mass function can be measured only in the solar neighbourhood, the constraints on SN II parents are not stringent. An estimate of the local SN II rate (e.g. Tammann, 1974) tells us that all stars more massive than 5 to 10 $M_\odot$ must become supernovae, and Kennicutt (1984) found that SN II's in Sc galaxies come from stars with masses greater than $8 \pm 1\ M_\odot$.

Since the fate of intermediate mass stars is mainly determined by mass loss in the red giant stage, the combination of stellar evolution tracks through the red giant stages with empirical red giant mass-loss rates also provides an estimate of M_{WD}. The difficulty of this approach is that while mass-loss rates in the normal red giant region are fairly well known and can be parametrized by semi-empirical interpolation formulae

---

* Formerly at Institut für Theoretische Physik und Sternwarte der Universität Kiel, F.R. Germany

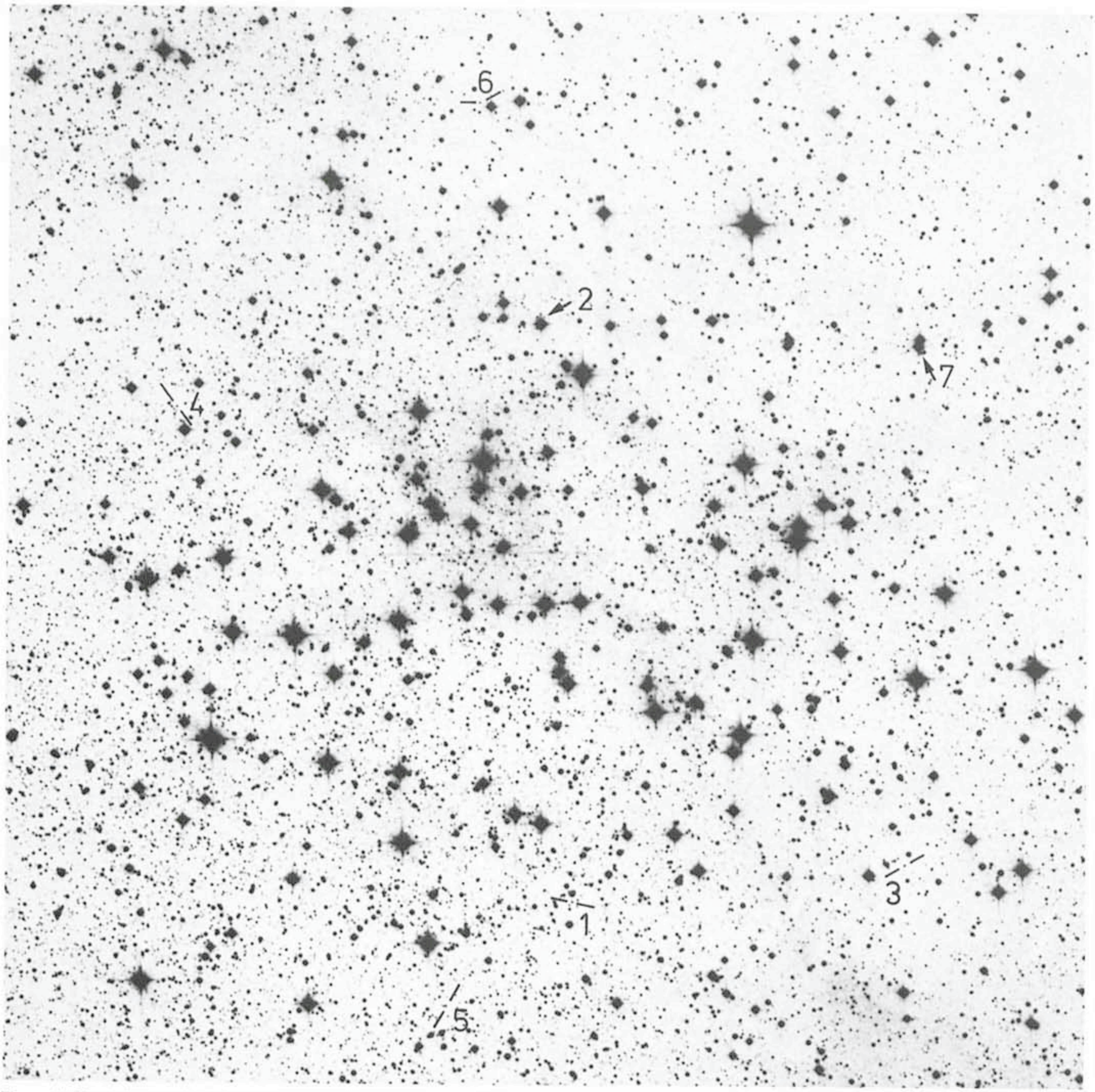

Figure 1: *Central part of NGC 3532 (ESO Schmidt, III a-J+UG1; 75 min) with marked positions of candidate objects.*

(e.g. $\dot{M} \sim L/g \cdot R$, Reimers, 1975, 1987), an extrapolation to advanced red giant phases (e.g. OH-IR stars) where most mass is lost is certainly not allowed. On the other hand, high mass-loss rates of advanced red giants as observed in thermal CO lines or in OH maser lines cannot easily be linked to stellar evolution calculations, since for these stars masses and evolutionary stages are poorly known.

The only reliable method to determine M_{WD} seems to be the identification of white dwarf members of galactic clusters with turn-off masses $M_t \lesssim M_{WD}$.

The first attempt with this method was made by v.d. Heuvel (1975) for the Hyades. He found $M_{WD} = 4\ M_\odot$. However, with a turn-off mass of $\sim 2\ M_\odot$ the Hyades are not favourable for this method since according to the cluster luminosity function, their known six white dwarf members must have had progenitor masses only slightly higher than the turn-off mass.

Faint Blue Objects in Open Cluster Fields

A new attempt to determine M_{WD} from cluster white dwarfs was made by Romanishin and Angel (1980) who looked for a statistical excess of faint blue objects – relative to comparison fields – in a number of intermediate age northern clusters. Based on their findings, they concluded $M_{WD} \approx 7\ M_\odot$. However, the question remained whether the excess of blue objects in the cluster fields were really white dwarfs. Anticipating the results of our spectroscopic observations over the years 1980–88 from both La Silla and Calar Alto of all Romanishin and Angel's candidates, it finally turned out that only 6 out of 17 WD candidates in the four clusters NGC 2168, 2242, 2287 and 6633 are cluster members. This means that without time consuming spectrophotometry of the faint ($V \approx 19$ to 21) blue objects in the cluster fields, no safe

Confirmed white dwarf members of intermediate age clusters

Cluster (Paper No.)	Age log T	Turn-off Mass	White Dwarf	T_e [10^3 K]	V	Mass [$M_{\odot}$]	Progenitor Mass [$M_{\odot}$]
NGC 2516 (II)	8.0	4.75	−1 −2 −5	30 36 34	19.6 19.55 20.1	0.95 1.14 1.17	7.2 7.6 9.8
NGC 2451[4] (III)	7.8	5.3	−6	31	16.75	0.6:	5.9
NGC 3532 (V)	8.3	3.6	−1 −5 −6	28 28 29	19.55 19.2 19.9	0.9 0.6 0.9	4.1 3.9 4.1
NGC 2168 (IV)	8.0	4.75	−3 −4	38 44	20.25 20.05	0.7 0.7	5.9 5.9
NGC 2287 (I)	8.25	3.9[1]	−2 −5	25 25	20.1 20.1	0.6 0.6	
NGC 6405 (VI)	7.9:	5.3:	−1[3]	82	18.1	1.18	6.5:
Pleiades	7.9	5.3	LB 1497			0.85	6.2[2]

[1] According to Romanishin and Angel (1980).

[2] Weidemann (1987).

[3] Cluster membership uncertain, WD is ~1° from cluster centre.

[4] NGC 2451 contains two more probable WD members (Paper III), if confirmed they have high masses and high progenitor masses; : denotes uncertain or preliminary values

conclusions are possible. The results of the first two observing years have been described briefly by Koester (1982).

Parallel to this activity we asked for deep ESO red and UV Schmidt plates of suitable southern intermediate age clusters with turn-off masses around 5 $M_{\odot}$. White dwarf members of clusters younger than about $2 \cdot 10^8$ years cannot have cooled down below about 25,000 K. Therefore one has to search for very blue faint objects in the cluster fields. With typical distance moduli of rich clusters between 8 and ≥ 11, hot white dwarfs are expected in the range V = 19 to 22.

The plates were blinked at Hamburger Sternwarte and we could identify further suitable candidates in the clusters NGC 2516, 2451, 3532, 6405, 6475, 6087 and IC 2391. Progress in follow up spectroscopy was slow, since due to the faintness of the objects only the 3.6 m + IDS was suitable in the years 1980–84, and the faintest objects as well as objects with relatively weak lines had to wait for EFOSC with its improved sensitivity. Our first observing run with EFOSC was conducted in April 88.

Cluster Membership

Even if a faint blue object within the cluster field turns out to be a white dwarf, it is not necessarily a cluster member. How can foreground and background white dwarfs be separated from cluster members? Besides the fact that extremely hot white dwarfs ($T_e >$ 30,000 K) are extremely rare in the general field and projection onto a cluster is therefore highly improbable, two criteria are applied: (i) the theoretically calculated cooling time, which depends on mass M and temperature T_e must be smaller than the cluster age and (ii) the distance modulus V-M_v determined from the observed apparent magnitude V and from effective temperature T_e and radius R has to be consistent with the observed cluster modulus. As Chandrasekhar's work, which won him the Nobel prize, has shown, degenerate stars obey a mass-radius relation which is approximately $R \sim M^{-1/3}$. The white dwarf radius R which is needed for cluster membership test is determined in the ideal case from gravity which can be measured from high-quality spectra by comparison with model atmosphere calculations. This was possible, e.g., in cases of NGC 2516 and NGC 3532. If gravity cannot be determined spectroscopically with sufficient accuracy, a typical WD mass is assumed in a first approximation. In most cases a decision about cluster membership is then possible since for a given effective temperature T_e the absolute magnitude varies as $M_v \sim R^2 \sim M^{-2/3}$ with mass, and assumptions about WD masses which have a narrow range anyway are not too crucial. As long as consistency with the cluster modulus is found for an assumed WD mass in the range 0.5 $M_{\odot}$ to 1.2 $M_{\odot}$, cluster membership is highly probable for a hot WD. Unfortunately, it will be difficult to measure proper motions of WDs in cluster fields at such faint magnitudes ($\sim 20^m$) in the near future.

The Present Status

How many white dwarf members of intermediate age clusters (turn-off masses $\gtrsim 4$ $M_{\odot}$) are known at present after the spectroscopic observations with the 3.6-m + IDS in the years 1980–84, the new start with EFOSC on fainter objects in 1988, and a few nights on the northern clusters NGC 2168 and NGC 6633 with the Calar Alto 3.5-m telescope? Altogether we have identified 12 (possibly 14) WD members of intermediate age clusters (Papers I–VI). Four were from Romanishin and Angel's (1980) candidate list (two in both NGC 2287 and NGC 2168). Eight (ten) hot DA white dwarfs (the hottest has 82,000 K!) have been discovered by ourselves on the ESO Schmidt plates taken for that particular purpose. Only one WD, the Pleiades member LB 1497 (e.g. Greenstein, 1974), was known to be member of an intermediate age open cluster before we started this project in 1980. ESO's superb equipment and dark sky has thus made possible an important contribution to an understanding of the final stages of stellar evolution.

Our first observing run with EFOSC and the 3.6-m telescope in April 1988 conducted by D.K. was highly successful. We identified 3 WD members of NGC 3532. Furthermore, we completed observations on several candidates in the clusters NGC 2422, 2516 and 2287 which had been too faint for an unambiguous identification with the IDS on the 3.6-m in earlier observing runs. The candidate in NGC 2422 could be proven to be a subdwarf, as suspected earlier (Paper I). The same applies to NGC 2516-4.

A highlight of the April 88 observations was the discovery of the extremely hot DA NGC 6405-1 (82,000 K, the hottest known DA?). While the star is ~1° outside the cluster centre, it has the same distance according to the model atmosphere analysis. One may suspect that the near coincidence of such an extremely rare type of star with a cluster is not just by chance.

A further surprise was that one of our faint blue candidates in NGC 6087 turned out to be a planetary nebula. It has a hot featureless continuum and nebular lines that extend ~14 arcsec in the direction of the spectrograph slit. A rough estimate shows that at the distance of the cluster (850 pc) this corresponds to a linear diameter of ~0.03 pc. This would imply a rather young PN with a central star of $M_v \approx -3$ to -4, inconsistent with the observed V magnitude of 19.3. Conclusion: Unfortunately, the PN is a background object.

M_{WD} and the Initial-Final Mass Relation

Data on the individual cluster white dwarfs identified by our spectroscopic observations and on the open clusters are compiled in the Table.

A major uncertainty for the determination of cluster turn-off masses, cluster ages and white dwarf progenitor masses has been recognized in recent years: the amount of convective overshooting for intermediate mass main sequence stars is not known. We have always assumed here an overshooting parameter $\alpha_C = 0.5$. For a full discussion of this point, in particular the influence of overshooting on the initial-final mass relation, we refer to Weidemann (1987).

The best case for determining M_{WD} is the rich southern cluster NGC 2516 (Reimers and Koester, 1982). Using the observed cluster luminosity function, the mass-interval above the cluster turn-off was estimated out of which the observed number of evolved stars has come. The result was $M_{WD} = 8^{+3}_{-2}\,M_\odot$. This statistical method, however, demands that no mass segregation has occurred within the cluster due to dynamical evolution. In cases where it is observed that the massive stars are more concentrated to the cluster centre than the low mass stars as in the case of the Hyades or NGC 3532, the statistical method can give only a lower limit to M_{WD} (Paper V), since for a sufficiently short relaxation time the white dwarfs can have a space distribution different from that of their progenitor stars or the upper main sequence stars respectively. An alternative approach is to try to estimate the WD progenitor masses by virtually placing the white dwarfs back onto the main sequence taking into account main sequence and red giant lifetimes and the WD cooling ages. For details we refer to Weidemann (1987). Thus obtained progenitor masses (Table) yield both an initial-final mass relation (Fig. 3) and an estimate of M_{WD}. Notice in Figure 3 that the initial-final mass relation may well be a strip with a finite width, which could be explained by differential mass-loss in the preceding red giant stage. Clearly more stars and more accurate data are needed, so, e.g., the accuracy of WD masses (via radii) depends on the accuracy of distance moduli and reddening corrections of open clusters!

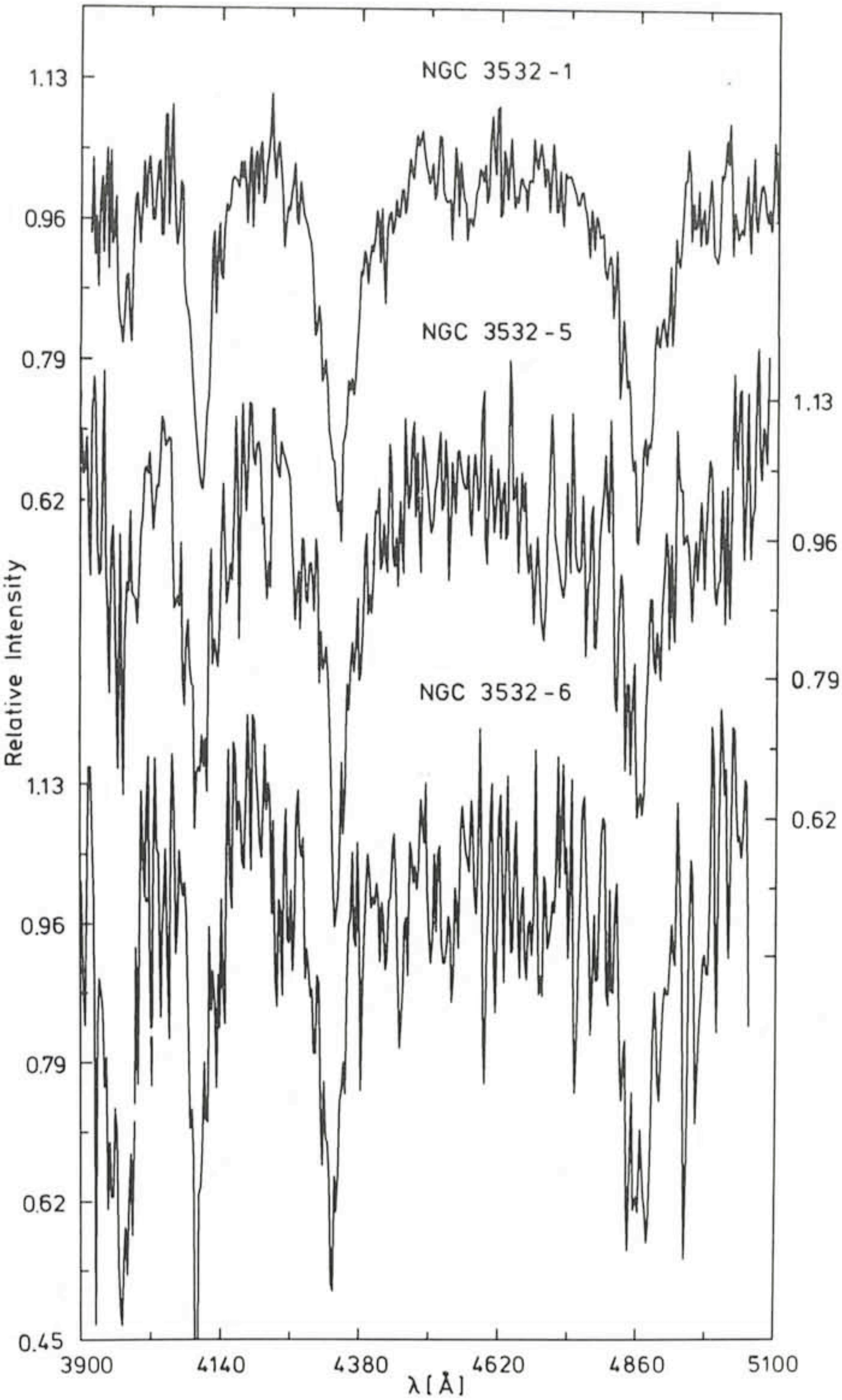

Figure 2: *EFOSC spectra of DA white dwarf members of NGC 3532.*

The Future

We clearly need more WD members of rich open clusters with turn-off masses above 5 $M_\odot$. One of the best known examples is NGC 6067, also called the "jewell box" because of its concentration of blue main sequence stars and red giants. It contains ~ 10 red giants and Cepheids. Due to its extreme richness and a turn-off mass of ~ 6 $M_\odot$ we expect about 15 hot white dwarfs in the cluster, however, at $V \sim 23^m$. Our attempt to find candidates with deep CCD exposures with the Danish 1.5-m telescope has so far been unsuccessful mainly due to the concentration of bright stars which caused severe CCD overflows. Due to the higher resolution of the CCD, EFOSC images look better.

Follow-up spectroscopy of 23^m candidates at a sufficient S/N for gravity determination using the model atmosphere technique will be a promising task for the VLT.

Acknowledgements

This work would have been impossible without the efficient support of

staff astronomers and skillful night assistants on La Silla.

References

Greenstein, J.L., 1974, *Astron. J.* **79,** 964.
Kennicutt, R.C., 1984, *Astrophys. J.* **277,** 361.
Koester, D., 1982, *The Messenger* **28,** 25.
Koester, D., Reimers, D., 1981, *Astron. Astrophys.* **99,** L8 (I).
Koester, D., Reimers, D., 1985, *Astron. Astrophys.* **153,** 260 (III).
Koester, D., Reimers, D., 1989, *Astron. Astrophys.* Letters, in prep. (VI).
Reimers, D., 1975, *Mem. Soc. Roy. Sci. Liège* **8,** 369.
Reimers, D., 1987, in *Circumstellar Matter,* IAU Symp. **122,** 307.
Reimers, D., Koester, D., 1982, *Astron. Astrophys.* **116,** 341 (II).
Reimers, D., Koester, D., 1988, *Astron. Astrophys.* **202,** 77 (IV).
Reimers, D., Koester, D., 1989, *Astron. Astrophys.* (V).
Romanishin, W., Angel, J.R.P., 1980, *Astrophys. J.* **235,** 992.
Tammann, G.A., 1974, in Supernovae and Supernova Remnants (C.B. Cosmovici, ed.) D. Reidel, p. 155.
v.d. Heuvel, E.P.J., 1975, *Astrophys. J.* **196,** L121.
Weidemann, V., 1987, *Astron. Astrophys.* **188,** 74.

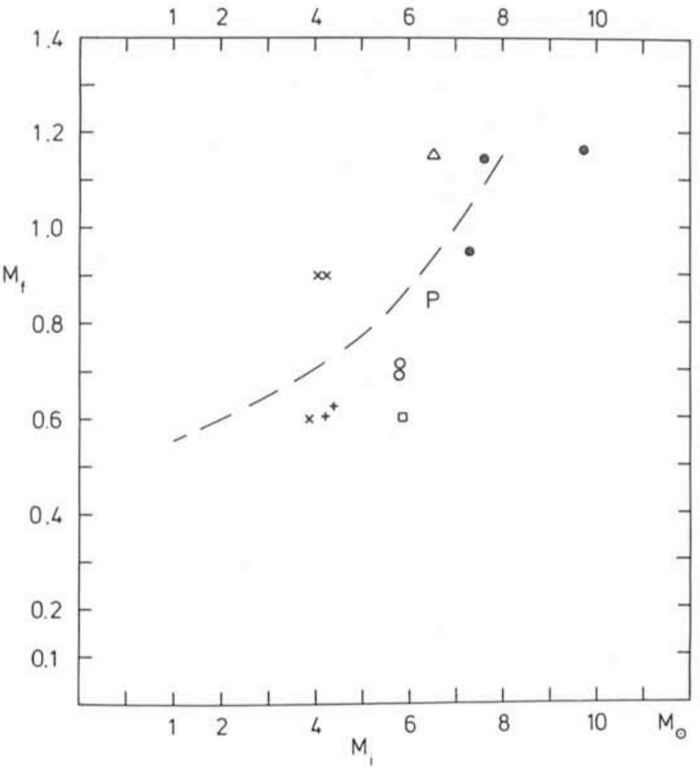

Figure 3: *Initial-final mass relation for intermediate-mass stars according to cluster white dwarfs identified in the course of this programme. Symbols: ○ NGC 2516, + NGC 2287, x NGC 3532, ° NGC 2168, □ NGC 2451, △ NGC 6405, P Pleiades. The broken line is the relation adopted by Weidemann (1987).*

New Results About SB0 Galaxies

D. BETTONI, Osservatorio Astronomico di Padova, Italy, and
G. GALLETTA, Dipartimento di Astronomia, Università di Padova, Italy

We discuss here the preliminary results of a long term project on kinematics and photometry of SB0 galaxies begun at ESO in 1983 and not yet fully completed. Beginning this study, we were particularly interested in analysing the mark of triaxiality that the bar induces in otherwise symmetrical galaxies, by perturbing and stretching out the stellar orbits. But we did not imagine that, progressing in this almost unexplored land, so many new and not yet fully explained features would be discovered. Now, we feel it would be interesting to resume here before the completion of the search the main results so far obtained.

1. A Bit of History

SB0 galaxies are good candidates for this study because of the low, but not negligible, quantity of gas and dust present in them. But despite the large number of theoretical models of bars, and the several works on gas kinematics, stellar motions were in the past very little studied. A systematic attempt to analyse the kinematics of SB0s (Kormendy 1982, 1983) was never completed and practically only one galaxy, NGC 936 (Kormendy 1983, 1984), was studied in detail (photometry, stellar velocity field and velocity dispersion field) before 1987. Similar projects at other observatories followed the same course, with observations never completed or results never published. Probable reasons for this were the difficulty of supporting for many years a project requiring many observing nights against the idea that in the melting pot of billions of stars moving within the bar it should be impossible to distinguish between "families" of orbits and, last but not least, against the occasional misunderstanding of some (too human) time commissions. But with some vicissitudes and a little bit of luck, observations of SB0s continued at ESO telescopes, demonstrating that we can look inside the stellar and gas kinematics with good hope of progressing toward its complete understanding. In recent years, therefore, new data on stellar kinematics have become available for eight more SB0s (Galletta 1987, Bettoni and Galletta 1988, Bettoni et al. 1988, Jarvis et al. 1988, Bettoni 1988). The observational techniques used in our observations reflect the improvement of ESO instrumentation in these years: starting with the 3.6-m telescope with the Boller & Chivens spectrograph and the 3-stage EMI image tube, the observations continued at the ESO-MPI 2.2-m telescope with RCA CCDs when these detectors became available. Parallel to this study, the inner photometry of the selected galaxies has been performed using the ESO-Danish 1.52-m telescope.

2. Observations and Data Reduction

Our sample includes 15 SB0 galaxies brighter than the 12th magnitude and