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# Commission 35: Stellar Constitution

**PRESIDENT: Wojciech A. Dziembowski**
**VICE-PRESIDENT: Francesca D'Antona**
**ORGANIZING COMMITTEE: C. Charbonnel, J. Christensen-Dalsgaard, J. Guzik, N. Langer, R. Larson, J. Liebert, G. Meynet, E. Müller, H. Saio, and D. VandenBerg**

**Abstract.** Ihe triennial report from Commission 35 covers its organizational activities and highlights accomplishments in various topics of stellar interior physics.

**Keywords.** sun: composition, helioseismology, stars: interior, rotation, oscillations, evolution

## 1. Introduction

The commission home page (`http://iau-c35.stsci.edu`), which is maintained by Claus Leitherer, contains information on forthcoming and planned conferences supplied by proposers. There are also convenient links to resources that were made available by the owners. The resources contain evolutionary tracks and isochrones from various groups, nuclear reaction, EOS, and opacity data, as well as links to main astronomical journals.

As a routine activity, the Organizing Committee has commented on and ranked proposals for several IAU sponsored meetings. At the forthcoming XXVIth IAU General Assembly in Prague there will be two Symposia and three Joint Discussions sponsored by our commission.

Members of Commission 35 were involved in organization of following IAU sponsored meeting during the three-year period covered by this report: IAU Symposium 215, Cancun (Mexico), November 2002, *Stellar Rotation*; IAU Colloquium 192, Valencia (Spain), April 2003, *Supernovae (10 years of SN1993J)*; IAU Colloquium 193, Christchurch (New Zealand), July 2003, *Variable Stars in the Local Group*; XXVth General Assembly, Sydney, July 2003: *Astrophysical Impact of Abundances in Globular Cluster Stars (JD04)*, *White Dwarfs: Galactic & Cosmological Probes (JD05). Solar & Stellar-like Oscillations: Insights & Challenges for the Sun & Stars (JD12) Elemental Abundances in Old Stars and Damped Lyman-Alpha Systems(JD15)*; IAU Symposium 224, Poprad (Slovakia), July 2004, *The A-Star Puzzle*; IAU Symposium 227, Catania (Italy), May 2005, *Massive Star Birth: A Crossroads of Astrophysics*; IAU Symposium 228, Paris, May 2005, *From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution.*

There were other meetings in which members of the commission were involved: *3D Stellar Evolution*, Livermore (California), July 2002; *Nuclei in the Cosmos-VII*, Fuji-Yoshida (Japan), July 2002; *Cosmic Explosions in Three Dimensions*, Austin (USA), June 2003; *CNO in the Universe*, St Luc (Switzerland), October 2002; *Physics and Astrophysics of Neutron Stars*, Santa Fe (USA), July 2003; *The Future Astronuclear Physics* Brussels (Belgium), August 2003; *Nuclear Astrophysics XII*, Ringberg Castle (Germany), March 2004; *Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis*, Austin (USA), June 2004; *Supernovae as Cosmological Lighthouses*, Padua (Italy), June 2004; *14th European Workshop on White Dwarfs*, Kiel (Germany), July 2004; *Nuclei in the Cosmos-VIII*, Vancouver (Canada), July 2004; *Stellar Pulsation and Evolution*, Monte Porzio (Italy), June 2005.



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The survey of advances in the field of stellar physics which is presented in the subsequent sections of this report was prepared by different members of the the Organizing Committee. Their names are acknowledged in the section headings.

## 2. High-mass stars (G. Meynet)

The question of the formation and evolution of Pop III stars still remains a very active area of research (see the review by Bromm & Larson 2004). In recent years, abundances at the surface of extremely metal poor halo stars have been measured (see the review by Beers & Christlieb 2005). These observations give insights on the stellar yields of the first massive star generations and pose many puzzling problems: for instance, how to explain the very small scatter of the abundances of many elements at very low $Z$; why are the peculiar chemical signatures of Pair Instability Supernovae not seen; Can very metal poor massive stars account for the high level of primary nitrogen enrichment required by the observations? Obviously, the answer to all these questions will bring new insights on the early chemical evolution of the galaxies.

The process of formation of massive stars has also received much attention in the past three years. Do massive stars form by merging (Bonnell & Bate 2005) or do they form in the same way as low-mass stars through accretion? Recent observations of disk-like structures centered on a massive protostar (Patel *et al.* 2005) would favor the latter scenario. From a theoretical point of view, accretion through a disk greatly reduces the radiation pressure experienced by gas in the in-falling material. Recently, Krumholz *et al.* (2005) showed that outflows with properties comparable to those observed around massive stars lead to a significant anisotropy in the radiation field, which also greatly reduces the radiation pressure.

The galaxies of the Local Group offer the opportunity to study massive star evolution at various metallicities, in different environments (see Massey (2003) review). Recently new spectroscopic and photometric observations of the young super star cluster Westerlund 1 revealed a rich population of Wolf-Rayet stars, OB supergiants and short lived transitional objects (Luminous Blue Variables, extreme B supergiants, yellow hypergiants and red supergiants). This cluster is presently the most massive compact young cluster identified in the Local Group, with a mass exceeding that of Galactic Center clusters. Its mass is consistent with expectations for a Globular Cluster progenitor.

Magnetic fields might also become an important topic in massive star evolution. Detections of magnetic fields have been reported in a number of hot stars (see the review by Henrichs et al. 2005). Values of a few hundred G up to slightly more than 1 kG have been measured. The question of the origin of these magnetic fields remains an open problem. Recently Mullan & MacDonald (2005) explored the possibility that a dynamo process occurring in radiative layers is responsible for these surface magnetic fields. Stellar evolution models accounting for similar dynamo processes have been computed (Heger *et al.* 2005; Maeder & Meynet 2005). Such models are able to extract more efficiently the angular momentum from the stellar cores than rotating models without magnetic fields, and a better fit to the observed rotation rates of young pulsars is obtained.

The hypothesis that the progenitors of the long soft gamma ray bursts (GRB) are massive stars has received a new impulse since the non-ambiguous identification of the spectrum of a type Ic SN in the afterglow of the GRB030329 (Mazzali *et al.* (2003)). According to the collapsar scenario (Woosley 1993), at least three conditions should be fulfilled by the progenitor for giving birth to a GRB: (i) to form a BH, (ii) to retain sufficient angular momentum in the central regions for allowing the formation of an accretion disk, (iii) to lose the H-rich envelope. The necessity to lose mass and, at the

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same time, to retain sufficient angular momentum are not conditions easy to meet. On the other hand, GRB are very rare events requiring some special circumstances to occur. Others explored the possibility that their progenitors followed an homogeneous evolution due to very fast rotation (Yoon & Langer 2005; Woosley & Heger 2005).

This small section does not allow us to cover many other interesting questions relevant to massive star evolution which were discussed in the literature during the last three years For more information on massive star evolution, the interested reader may consult the web page of the the IAU working group on massive stars (`http://www.astroscu.unam.mx/massive_stars/`). Much very useful information, regularly updated, can be found there as links to the *Massive Star Newsletter*, to conference web pages, and to databases.

## 3. Low-Mass Stars (D. VandenBerg)

In the area of low-mass stars, recent results pertaining to diffusive and rotating stellar models deserve to be highlighted, along with efforts to understand the first stars that formed after the Big Bang. The primordial Li abundance implied by the concordance of WMAP and Big-Bang nucleosynthesis results initially appeared to be problematic because it was a factor of 2–3 larger than the Li abundances measured in the oldest Population II stars. However, Richard *et al.* (2005) have shown that their models, which allow for gravitational settling and radiative accelerations in the presence of weak turbulence, can explain much of this difference – suggesting that an improved understanding of turbulent transport in the radiative zones of stars may be all that is needed to completely explain the discrepancy. Diffusive models are also able to reproduce the turnoff morphology of the old open cluster M 67 without the need for any convective core overshooting at all (see Michaud *et al.* (2004)), and it seems likely that the "Li dip" observed among Hyades main-sequence stars can be explained in terms of the competition between gravitational settling and the circulation currents generated in slowly rotating stars (see Théado & Vauclair (2003)). In addition, the coupling between circulation currents and magnetic fields could well explain why the Sun has close to solid-body rotation between $\sim 0.2$ and $0.7 R_\odot$ (Eggenberger *et al.* (2005)). Another notable achievement is the fact that tracks for $\approx 0.8$–$2\mathcal{M}_\odot$ stars have now been extended to the tip of the giant branch (Chaname *et al.* (2005)), mainly for the purpose of addressing the observed chemical abundance anomalies in giants (see the section on mixing in stars, below).

The discovery of HE 0107-5240 (Christlieb *et al.* (2002)), which has $[\mathrm{Fe/H}] < -5$ and very large CNO abundances, lead Weiss *et al.* (2004) and Picardi *et al.* (2004) to examine whether large [CNO/Fe] ratios could be produced in initially metal-free stars as a result of the peculiar He core flash that occurs in Pop. III stars, or whether they are actually second-generation objects that formed out of a mixture of primordial material and ejecta from a single primordial supernova. Both investigations conclude that the first possibility does not seem to be viable, and thus suggest that the second alternative is the most promising one to explore further. Curiously, the observed $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratio in HE 0107-5240 presents difficulties for both scenarios. Motivated by the fact that stars with planets appear to be more metal rich than the average field star, Cody & Sasselov (2005) studied the general effects of planet consumption (also see Dotter & Chaboyer (2003)), but were unable to find any clear correlations of the properties of their models with those of stars known to possess planets. Nevertheless, the pollution of stars by the ingestion of planets (or by the the ejecta from supernova or asymptotic giant branch stars, see below) must certainly occur. We note, finally, that the latest large grids of tracks and isochrones for application to studies of stellar populations are those by Pietrinferni *et al.* (2004).

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## 4. AGB Stars (F. D'Antona)

We refer to the review by Herwig (2005) for detailed and complete references to most of the theoretical research of the years 2002–2005 on AGB evolution. The problem of the third dredge-up and its consequences for the formation of Carbon stars and for the associated s–process nucleosynthesis is still treated in a parametric way, but many hints are now quantified about the dependence of its efficiency (defined by the parameter $\lambda$) on the input physics, such as efficiency of convection, mass loss and, notably, even on the nuclear reaction rates (Herwig 2004). Study of s–process production has been mainly concentrated on the role and extension of the $^{13}$C pocket in low mass AGBs (e.g. Lugaro *et al.* 2003 or Siess *et al.* 2004). The work of Nollett *et al.* (2003) concentrates on the effect of the non standard mixing process called "cool bottom processing" (CBP) on important isotopic ratios such as $^{18}O/^{16}O$, $^{17}O/^{16}O$, $^{15}N/^{14}N$, $^{26}Al/^{27}Al$, C/O, and N/O during the AGB phase of a 1.5M$_\odot$ star. Attention has been devoted to the study of the fast evolutionary phases of post-AGBs (Hajduk *et al.* 2005) and interpretation of the detailed chemistry of the hot PG 1159 objects (e.g. Lugaro *et al.* 2003).

There has been considerable interest in the most massive AGB stars. These stars evolve in the early life of globular clusters (GCs) and eject their envelopes processed by Hot Bottom Burning (HBB). This matter gives to second generation stars in the clusters, producing pattern of abundances known as chemical anomalies among GC stars (D'Antona & Da Costa (2004)). Some GC data, such as the lithium abundances in these stars (Gratton *et al.* (2004)) and the peculiar morphologies of some horizontal branches (D'Antona & Caloi (2004)), strongly favor this scenario, but the modeling of some chemical anomalies (e.g. the O–Na and Mg–Al anticorrelations, the constancy of the global CNO abundances) are not in agreement with the GC data, casting doubts about the reliability of the self–enrichment models (Fenner *et al.* (2004), Herwig (2004).

On the contrary, some researchers are convinced that the AGB modeling is not adequate and the scenario of self–enrichment is correct. Ventura & D'Antona (2005) have recently shown that the yields of HBB nucleosynthesis are very poorly constrained, as they change by orders of magnitude by changing the efficiency of convection in the AGB– and, indirectly, the efficiency of mass loss. The self–enrichment scenario requires that the HBB phase is modeled by a very efficient convection model, such as the Full Spectrum Turbulence model of Canuto, Goldman, & Mazzitelli(1996).

## 5. Supernovae (E. Müller)

The precise scenario of SNe Ia which are commonly attributed to thermonuclear explosions of Chandrasekhar-mass C+O white dwarfs in a binary system is still controversial although substantial progress has been achieved during the past three years (e.g. Hillebrandt (2004)), particularly through the development of 3D models of thermonuclear supernova explosions (Reinecke (2002), Gamezo *et al.* (2003), Travaglio *et al.* (2004), Röpke & Hillebrandt (2004), Gamezo *et al.* (2005), Röpke (2005), Röpke & Hillebrandt (2005a), Röpke & Hillebrandt (2005b)). The most advanced of these models (Röpke & Hillebrandt (2005b)) has considerable predictive power and allows one to study observable properties of SNe Ia, such as their light curves and spectra, without adjustable non-physical parameters, and allows for firm predictions of the nucleosynthesis yields (Travaglio *et al.* (2004)) from the explosions. The new 3D models have stimulated a quest for better data, covering the spectroscopic and photometric evolution in all wave bands from very early epochs all the way into the nebular phase. Such results have been obtained

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by the European Supernova Collaboration (ESC; `http://www.mpa-garching.mpg.de/~rtn`) for a sample of nearby SNe Ia.

Progress in modeling core collapse supernovae was achieved by 2D radiation-hydrodynamic simulations with multi-frequency, multi-angle Boltzmann neutrino transport taking into account also the effects of rotation (Buras *et al.* 2004, Janka *et al.* (2005a), Janka *et al.* (2005b)). Even these up-to-now most sophisticated simulations fail to produce powerful explosions. However, they are very close to success, as some models showing weak explosions (Janka *et al.* (2005a)). The success of previous and recent 2D and 3D simulations with grey (e.g. Fryer & Warren (2004)) or multi-group (e.g. Walder *et al.* (2005)) flux-limited neutrino diffusion is therefore not confirmed. Whether these results suggest missing physics, possibly with respect to the nuclear equation of state and weak interactions in the sub-nuclear regime, or whether they indicate a fundamental problem with the neutrino-driven explosion mechanism requires further investigations (e.g. Buras *et al.* 2004, Janka *et al.* (2005b), Mezzacappa (2005)). It is now, however, generally agreed that 1D models with accurate neutrino transport and standard microphysics input fail to explode by the delayed, neutrino-driven mechanism for progenitors with $M > 10M_\odot$ (e.g. Liebendörfer *et al.* (2005)). Both 2D and 3D simulations of neutrino-driven convection show that hydrodynamic instabilities can lead to low-mode ($l = 1, 2$) flow asymmetries in the neutrino-heated layer behind the supernova shock wave (e.g. Blondin *et al.* (2003), Janka *et al.* (2005a)). This suggests a natural explanation for global asymmetries of observed core collapse supernovae and for observed pulsar recoil velocities (Scheck *et al.* 2004). Studies partially employing simpler microphysics and neutrino transport, or even no transport at all, focused on the effects of rotation (e.g. Fryer & Warren (2004), Ott *et al.* (2005)), magnetic fields (e.g. Akiyama *et al.* (2003), Yamada & Sawai (2004)) and on the gravitational radiation produced by core collapse supernovae (Müller *et al.* (2004), Ott *et al.* (2004)).

Another active area of research has been the investigation of the connection between supernovae/hypernovae and (long?) gamma-ray bursts driven by observations of SNe Ib/c coincident in space and time with observed GRBs (e.g. Hjorth *et al.* (2003), Mazzali *et al.* (2003)).

## 6. Transport processes in stars (C. Charbonnel)

Although the standard stellar models have been able to reproduce many observed features, it becomes clear now that non-standard transport processes of the chemicals and of angular momentum have to be included in the modern models in order to reproduce detailed data in several parts of the HR diagram. Rotation appears to be a key ingredient, together with internal gravity waves and magnetic fields.

New theoretical results by Mathis & Zahn (2004) have improved modeling of the rotational mixing which occurs in stellar radiation zones, through the combined action of thermally-driven meridional circulation and of turbulence generated by the shear of differential rotation. This will allow a simultaneous treatment of the hydrodynamical processes in the bulk of radiative zones and in the tachoclines.

Another delicate aspect concerns the treatment of turbulence in stars. Mathis *et al.* (2004) have reviewed various prescriptions which have been proposed for the turbulent transport of matter and angular momentum in differentially rotating stellar radiation zones. They present a new prescription for the horizontal transport associated with the anisotropic shear turbulence which is produced by the differential rotation in latitude; this "$\beta$-viscosity" is drawn from torque measurements in the classical Couette-Taylor experiment.

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Regarding main sequence stars, it was known for a long time that the classical hydrodynamical processes related to rotation, i.e., meridional circulation and shear turbulence, are insufficient to explain the internal rotation profile of the Sun as given by helioseismology. The incorporation of the internal gravity waves in hydrodynamical rotating models has helped solving this problem, and the corresponding models now explain both the solar rotation and the lithium abundance in main sequence stars over a large mass range (Talon & Charbonnel 2005; Charbonnel & Talon 2005).

Young *et al.* (2003) present an analysis of the response of a radiative region to waves generated by a convective region of the star; this wave treatment of the classical problem of "overshooting" gives extra mixing relative to the treatment traditionally used in stellar evolutionary codes. The interface between convectively stable and unstable regions is dynamic and nonspherical, so that the non-turbulent material is driven into motion, even in the absence of "penetrative overshoot". These motions may be described by the theory of nonspherical stellar pulsations and are related to motion measured by helioseismology. Multidimensional numerical simulations of convective flow show puzzling features, which are explained by this simplified physical model. Gravity waves generated at the interface are dissipated, resulting in slow circulation and mixing seen outside the formal convection zone. The approach may be extended to deal with rotation and composition gradients ("semiconvection").

Regarding internal gravity waves, many issues remain open: The excitation of the waves by the stellar convective zones (cores and envelopes), the effect of the Coriolis force, the interaction with magnetic fields, and the direct transport of chemicals. Progress should come from 2 or 3D simulations. For example, the excitation of internal gravity waves by penetrative convective plumes has been investigated using 2-D direct simulations of compressible convection by Dintrans *et al.* (2005). The wave generation is quantitatively studied from the linear response of the radiative zone to the plume penetration, using projections onto the g-mode solutions of the associated linear eigenvalue problem for the perturbations. This allows an accurate determination of both the spectrum and amplitudes of the stochastically excited modes.

Much effort has been done on the theoretical side for the treatment of rotation coupled to magnetic fields. In addition to the classical rotational mixing, which results from the combined action of the thermally-driven meridional circulation and of the turbulence generated by the shear of differential rotation, Mathis & Zahn (2005) have included the effect of an axisymmetric magnetic field in a self-consistent way. They treat the advection of the field by the meridional circulation, its Ohmic diffusion, and the production of its toroidal component through the shear of differential rotation. The Lorentz force is assumed not to exceed the centrifugal force; it acts on the baroclinic balance and therefore on the meridional flow, and it has a strong impact on the transport of angular momentum.

Many works regarding the impact of the processes described above have been done and published for stars on the main sequence. However the advanced stellar phases present many interesting and complementary constraints. From the observational point of view, many abundance anomalies both on the RGB and AGB point towards non standard transport processes. The role of rotationally induced mixing in the development of abundance anomalies in giants is difficult to assess and the current rotating RGB models make some very contradictory predictions (Denissenkov & VandenBerg 2003; Chamané *et al.* 2005; Palacios *et al.* 2005). However a general result is that after the completion of the first dredge-up, the degree of mixing is maximized in the case of a differentially rotating envelope, as anticipated in previous studies.

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## 7. Helio- and astero-seismology (W. Dziembowski)

The significance of helio-seismic models for whole astrophysics was again demonstrated in the wake of the downward revision by 25–35% of the photospheric C, N, and O element abundances in the Sun (Asplund *et al.* 2004). When these new abundance data were taken as representative for the overall heavy element abundance in solar modeling, a conflict with helio-seismic models became apparent. Bahcall *et al.* (2005) showed that the conflict could be resolved by an *ad hoc* 11% increase of opacity in the outer part of radiative interior. Subsequent solutions included significantly above standard Ne abundance (Antia & Basu 2005) as well as nonstandard element diffusion and accretion processes in the sun's evolution (Guzik *et al.* 2005). Drake & Testa (2005), who recently measured the Ne abundance in a sample of nearby solar-like stars from their X-ray spectra, found that the standard abundance has been underestimated on average by about a factor of 2.5. This result seems to confirm the solution proposed by Antia & Basu (2005).

Models constrained by frequency data (seismic models) were obtained for stars belonging to various types of multimode pulsators. The greatest interest was in modeling solar-like pulsators such as $\alpha$ Cen (Thoul *et al.* 2003), $\eta$ Boo (Di Mauro *et al.* 2004; Carrier *et al.* 2005), $\alpha$ CMi (Kervella *et al.* 2004; Eggenberger*et al.* 2005), and $\mu$ Arae (Bazot *et al.* 2005). The last object is an exoplanets host star and the primary goal was determination of its internal metallicity. Still there are mostly only promises for seismic constraints from solar-like oscillation data.

Seismic models were also calculated for two multimode $\beta$ Cephei stars: HD129929 (Dupret *et al.* 2004) and $\nu$ Eri (Pamyatnykh *et al.* 2004; Ausseloos *et al.* 2004). The models gave strong constraints on the convective overshooting from the core and evidences for inward rising rate of rotation. Charpinet *et al.* (2005) calculated a seismic model of the sdB pulsator PG 1219+534 yielding precise total mass and mass of the hydrogen envelope which determines evolutionary status of the object. Possible seismic evidence for rapidly rotating cores of sdB stars was considered by Kawaler & Hostler (2005).

Cunha *et al.* (2003) conducted a seismic test of models of the roAp star HR1217. Vauclair & Thado (2004) looked for a signature of helium gradients in the oscillation spectrum of HD 60435, another roAp pulsator. Saio (2004) examined effects of a magnetic field on the radiative excitation and the damping of p-modes in stars of this type.

Testing various aspects of white dwarfs with oscillation data was the subject of several papers. In particular, Metcalfe *et al.* (2004) constructed a seismic model of the massive white dwarf BPM 37093 finding the mass of its crystallized core in agreement with theoretical expectations. Prospects of accurate testing of diffusion theory and on neutrino cooling rates were considered by Metcalfe *et al.* (2005) and Winget *et al.* (2004), respectively.

Oscillation frequencies were not the only seismic observables that have been used to constrain stellar interior physics. Amplitudes and mode life times measured for $\alpha$ Cen were compared with predictions based on stochastic excitation theory (Bedding *et al.* (2004); Samadi *et al.*(2004)). Significant discrepancies with current models were found. Application of photometric and spectroscopic data on mode amplitudes and phases in $\delta$ Scuti oscillation spectra for testing models of the outer convective zone in A and F-type stars was proposed by Daszyńska-Daszkiewicz *et al.* (2003) and by Moya *et al.* (2004).

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Wojciech A. Dziembowski
*President of the Commission*

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