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COMMISSION 35: STELLAR CONSTITUTION
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1. Introduction

During the past three years, the main activities of Commission 35 were its participation in the Manchester General Assembly (in August 2000) and the on-going consideration of proposals for symposia and colloquia seeking IAU status and support. At the Manchester GA, our commission organized JD 5 ("Mixing and Diffusion in Stars: Theoretical Predictions and Observational Constraints"), and it supported JD 8 ("Oxygen Abundances in Old Stars and Implications for Nucleosynthesis and Cosmology") and JD 13 ("Hipparcos and the Luminosity Calibration of the Nearer Stars").

Many conferences and workshops were held during the report period on topics that fall within the scope of Commission 35: those of particular relevance are briefly referenced in §2. The remainder of this report gives a short review of several of the advances that have been made in our field of research since mid-1999. The members of the OC who kindly contributed to this review are acknowledged in the section headings.

2. Workshops, Colloquia, and Conferences

The proceedings of most astronomical conferences are now published in the ASP Conference Series. Below we give the titles (and volume numbers) of those proceedings of particular interest to members of Commission 35. Meetings held between July 1 and Dec. 31 of 1999 included "Pulsar Astronomy — 2000 and Beyond, IAU Colloq. 177 (vol. 202), "The Impact of Large-Scale Surveys on Pulsating Star Research, IAU Colloq. 176" (vol. 203), "Delta Scuti and Related Stars" (vol. 210), "Massive Stellar Clusters" (vol. 211), "From Giant Planets to Cool Stars" (vol. 212), "The Be Phenomenon in Early-Type Stars, IAU Colloq. 175" (vol. 214), and "Cool Stars, Stellar Systems, and the Sun: 11^{th} Cambridge Workshop" (vol. 223). Held in 2000 were "12^{th} European Conference on White Dwarfs" (vol. 226), "Evolution of Binary and Multiple Stars" (vol. 229), "P Cygni 2000: 400 Years of Progress" (vol. 233), "Eta Carinae and Other Mysterious Stars" (vol. 242), and "Interacting Winds from Massive Stars" (vol. 260). In 2001, the following meetings were held: "Young Stars Near Earth: Progress and Prospects" (vol. 244), "Astrophysical Ages and Timescales" (vol. 245), "The Central Kiloparsec of Starbursts and AGN" (vol. 249), "Radial and Nonradial Pulsations as Probes of Stellar Physics, IAU Colloq. 185" (vol. 259), "The Physics of Cataclysmic Variables and Related Objects" (vol. 261), "Stellar Collisions, Mergers, and Their Consequences" (vol. 263), "Hot Star Workshop III: The Earliest Stages of Massive Star Birth" (vol. 267), "Neutron Stars in Supernova Remnants" (vol. 271), and "Observed HR Diagrams and Stellar Evolution" (vol. 274). "Exotic Stars as Challenges to Evolution, IAU Colloq. 187" (vol. 279) was held in the first six months of 2002.

Also of interest, and published by the ASP, are the proceedings of IAU Symposia 198 ("The Light Elements and Their Evolution", held in 1999), 200 ("The Formation of Binary

Stars", in 2000), 207 ("Extragalactic Star Clusters", in 2001), 209 ("Planetary Nebulae: Their Evolution and Role in the Universe", in 2001), 211 ("Brown Dwarfs", in 2002), and 212 ("Massive Star Odyssey: From Main Sequence to Supernova", in 2002).

3. **Massive Stars** (G. Meynet)

Among the actively debated problems is the question of how the massive stars form (see ASP Conf. Ser. 267 and the proceedings of the recent MPA/ESO Workshop entitled "The First Stars" for the latest developments in this research area). At present, two scenarios for massive star formation have been proposed. Massive stars might form by the accretion of matter through an equatorial disk or via coalescence of intermediate-mass protostars. Both scenarios might occur in nature, perhaps with different efficiencies depending on the physical conditions. The fact that, during these early stages of formation, the nascent star is embedded in an optically thick cocoon of dust and gas, necessitates observations at radio, submillimeter, or infrared wavelengths. Such future facilities as the Space Infrared Telescope Facility (SIRTF) or the Atacama Large Millimeter Array (ALMA) will certainly provide new clues about this very poorly understood evolutionary stage.

How do massive stars evolve? The recent IAU Symposium 212 thoroughly discussed this question. The comparison between the predictions of standard stellar models with still more constraining observations clearly shows that extra-mixing processes are at work in massive stars, and that rotation appears to be a very promising mechanism for driving these mixing processes (see §8.1). Predicted surface rotational velocities can be compared with observed ones. In this respect, the measures of rotational velocities of stars at different metallicities will provide very interesting indications. The evolution of binaries accounting for the effects of rotation has also been explored.

Mass loss by stellar winds, and its dependence as a function of metallicity and surface rotation velocity, is a key feature of massive star evolution. Interacting winds of massive stars may be used, in principle, to trace the mass-loss history of a star from the surrounding "shells" left behind after various phases of interaction (see ASP Conf. Ser. 260). Massive stars are also known to be the progenitors of many "exotic stars", such as Be stars, Wolf-Rayet stars, and Luminous Blue Variables (see ASP Conf. Ser. 214, 233, and 242, respectively, for recent conferences on these objects), and they may well be the progenitors of gamma-ray bursters (Mészáros 2002). Finally, the importance of the study of young starbursts must be emphasized. These regions of high star formation rate are wonderful laboratories for investigating massive star evolution in different environments. Moreover, they constitute an important link between stellar and galactic evolution. Their possible relation with AGN phenomena remains a very topical subject (see ASP Conf. Ser. 249).

4. **Intermediate-Mass Stars** (J. Guzik)

A number of evolution studies of Population III ($Z = 0$) intermediate-mass stars have been carried out in the past three years (Dominguez et al. 2001; Chieffi et al. 2001; Siess et al. 2002), prompted by the detection of metals in different components of the high-redshift universe and the desire to explain abundance ratios of the most metal poor stars. Contrary to some previous claims, these recent results have confirmed that Pop. III stars can undergo normal thermal pulses, and that their envelopes can be enriched during dredge-up events. These stars have probably contributed significantly to the early Galactic enrichment of C and N, as well as the production of some Mg and Al (and possibly some s-process elements, even in the absence of Fe seed nuclei). These results will motivate a major re-examination of our picture of chemical evolution of the early Galaxy. Abia et al. (2001) discussed the implications of recent $Z = 0$ stellar models for yields and chemical enrichment, and concluded that low star formation efficiencies of $< 1\%$ are required to avoid exceeding the minimum $[C/H] \sim -2.4$ found in high-redshift systems for plausible initial mass functions (IMFs). To account for the large C,N to Fe ratios found in many extremely metal poor stars of our Galaxy, an IMF for Pop. III stars peaking at intermediate masses of 4–8 $\mathcal{M}_\odot$ is needed. Marigo et al. (2001) have predicted the pulsation properties of $Z = 0$ stars.

Another important contribution is that by Bono et al. (2000), who presented an extensive set of results for 3 to 15 $\mathcal{M}_\odot$ models, evolved from the ZAMS to central He exhaustion or the beginning of thermal pulses. They investigated the Y and Z dependences of the properties of blue loops and the evolution of Cepheids, as well as the upper mass limit for which stars develop electron-degenerate CO cores. In addition, Siess et al. (2000) computed new pre-main-sequence (PMS) tracks for 0.1 to 7 $\mathcal{M}_\odot$ stars with $Z = 0.01$–0.04, Marigo (2001) provided new predictions of the chemical yields for low- and intermediate-mass stars, and Guenther (2002) presented the evolution, structure, and predicted p-mode oscillations for 2 to 5 $\mathcal{M}_\odot$ models, showing how stellar mass, convective core and envelope growth and decay, composition gradients, and onset of shell H-burning may be diagnosable using future oscillation observations. Comprehensive investigations of the evolution of interacting binary systems have also been carried out (e.g., Han et al. 2002).

The topic of pre-main sequence A and B stars, including Herbig Ae and Be stars, remains a lively area of study. Stępień (2000) modelled the PMS rotational evolution of intermediate-mass stars having a primordial magnetic field, taking into account accretion, the field-disk interaction, and a magnetized wind. For a wide range of parameters, the ZAMS rotation periods of Ap stars turned out to be several times longer than for normal A stars, in good agreement with observations. Hinz et al. (2001) reported that the sizes of mid-IR emission regions of nearby Herbig Ae stars may be much smaller than current models predict. Marconi et al. (2000) derived periods and pulsation modes for δ Scuti-type pulsations in two Herbig Ae stars, and discussed how nonlinear pulsation models can be used to place some constraints on their masses.

4.1. AGB Stars (F. D'Antona)

The review by Busso et al. (1999) and the proceedings of meetings entitled "The Changes in Abundances in AGB Stars" (2000, Mem.Soc. Astron. Ital., 71, No. 3) and "Salting the Early Soup: Trace Nuclei from Stars to the Solar System' (2001, Mem. Soc. Astron. Ital., 72, No. 2) presented much of our current understanding of the structures of, and nucleosynthesis in, AGB stars (also see Lattanzio 2002). Although the extent of the third dredge-up continues to be quite uncertain, and will remain so until a full understanding of Carbon stars is achieved, promising new results on the formation of C stars and H-deficient white dwarf progenitors, as well as the production of s-process elements, have been reported by Herwig et al. (1999) and Herwig (2000), using stellar models that allow for convective overshoot and time-dependent mixing. In addition, Ventura et al. (2001) showed that "hot bottom burning" proceeds at temperatures above 10^8 K in massive AGB stars of low metallicity (and hence that the AGB may be the most plausible site for the primordial chemical abundance variations seen in globular cluster stars). Finally, we note that the role of AGB stars in galactic lithium evolution is still uncertain (see the different approaches by Ventura et al. 2000, and Travaglio et al. 2001).

5. Low-Mass Stars (D. VandenBerg)

First results from the Sudbury Neutrino Observatory (SNO) have served to confirm the basic correctness of stellar evolutionary theory. As reported by Ahmad et al. (2002), SNO has obtained direct evidence for neutrino flavor transformations and found very good agreement between the measured and predicted flux of ^{8}B neutrinos from the Sun. To be sure, many issues (see §8) need to be resolved before we can claim to have more than a good basic understanding of the structures of the Sun and stars of similar mass.

Of the stages in the life of a low-mass star, the red-giant phase has been subjected to the most scrutiny during the past three years. Salaris et al. (2002) have written an excellent review of this evolutionary phase, including a thoughtful discussion of the successes and failures of continuing attempts to explain surface abundance anomalies. In this regard, Aikawa et al. (2001) have argued that the shell flashes that would result from deep mixing into the He core (were such mixing to occur) could explain the observed abundance variations of ^{24}Mg, ^{23}Na, and ^{27}Al — though it is not yet clear whether such variations are primordial or due to evolutionary processes. Weiss et al. (2000) concluded that anomalies in lighter elements can be completely explained by deep mixing between the convective envelope and the H-burning shell. Sugimoto & Fujimoto (2000) and Schrinner & Deinzer (2001) have added further fuel to the current debate about why stars become red giants.

The most recent grids of evolutionary models and isochrones for the interpretation of stellar data are those by Girardi et al. (2000), Bergbusch & VandenBerg (2001), and Yi et al. (2001). To facilitate the treatment of stellar evolution in n-body codes, Hurley et al. (2000) have produced comprehensive analytic formulae, based on Cambridge tracks, to describe the evolution of stars for a wide range in Z from their main-sequence to their remnant stages. As far as globular cluster (GC) ages are concerned, the most sophisticated models computed to date for very metal-deficient stars (by Richard et al. 2002) yield an age of 13.5 Gyr for M 92 (see VandenBerg et al. 2002), which appears to be consistent with the age for the universe derived from the Cosmic Microwave Background. Whether or not GC ages vary significantly with metallicity seems to depend mostly on which of the available [Fe/H] scales is used for these systems (see Salaris & Weiss 2002). (Note that many timescale issues were discussed in a recent conference; see ASP Conf. Ser. 245.)

6. Very Low Mass Stars, Brown Dwarfs, and Giant Planets (F. D'Antona)

The theory of very low mass stars and substellar objects has been recently reviewed by Chabrier & Baraffe (2000), who discuss improved computations for the structures of these objects and comparisons with observations. The latest reviews of theoretical models for brown dwarfs and giant planets are those by Burrows et al. (2001) and Hubbard, Burrows, & Lunine (2002): they describe not only the evolution, atmospheric composition, and spectra of these objects (particularly those comprising the new spectroscopic L and T classes), but also the effects of condensates, clouds, molecular abundances, and atomic opacities (which are important for an understanding of their spectral properties). Over the past 3 years, important advances have been made in the construction of complex model atmospheres (Allard et al. 2001; Tsuji 2002) for the "dusty" L-type dwarfs to the (probably) grain-free T-dwarfs ($T_{eff} < 1400$K). Some work has also been done to explore the implications of these atmospheres for evolutionary models (e.g., Chabrier et al. 2000).

Stimulated by the observation of giant planet transits, many studies have been carried out to study the effects of irradiation on giant planet companions of stars (see e.g., Hubbard et al. 2001). Perhaps the most intriguing recent result concerning young brown dwarfs is that obtained by Natta & Testi (2001), who showed that the emission observed from a few young objects in Chamaeleon is well described by models allowing for circumstellar disks similar to those associated with T Tauri stars. It therefore seems to be the case that the formation mechanism of T Tauri stars (via core contraction and formation of an accretion disk) extends to objects in the brown dwarf mass range.

7. White Dwarfs (G. Vauclair)

Following the claim (Méndez & Minniti 1999) that micro-lensing events and faint blue objects in the *HST* deep fields could be due to halo cool white dwarfs (WDs), making the halo WD population a significant contributor to the baryonic dark matter, considerable efforts have been devoted to the study of cool white dwarfs. This includes several systematic searches (Ruiz & Bergeron 2001, and references therein), detailed studies of individual WDs (e.g., Scholz et al. 2002), and new theoretical calculations of WD cooling sequences (e.g., Hansen 1999; Chabrier et al. 2000). However, the identification of these cool white dwarfs with the halo population is controversial, as some fraction of them could belong to the thick disk (Reid et al. 2001). Number constraints also argue against the association of white dwarfs with MACHO events (Fields et al. 2000). Nevertheless, discovering new extremely cool white dwarfs remains a major goal because of their great age and the constraints that they place on the ages of their parent populations. However, uncertainties in the mass of their hydrogen- or helium-rich outer layers (Bergeron et al. 2001) and in the description of the crystallisation phase (Montgomery et al. 1999; Isern et al. 2000) still preclude an age determination more precise than ≈ 2 Gyr (Fontaine et al. 2001). These uncertainties affect, as well, the attempts to determine distances and ages of open and globular clusters by using their WD cooling sequences (e.g., H. B. Richer et al. 2000; Zoccali et al. 2001).

Determining the atmospheric parameters of the hottest white dwarfs is still a very active field since high-resolution spectroscopy from space (*HST*, *FUSE*) gives access to the UV, FUV and EUV domains. A large number of hot white dwarfs with photospheric heavy elements have been found and their abundances put more constraints on radiative levitation theory (Dreizler 1999; Friedrich et al. 1999; Wolff et al. 2001; Barstow et al. 2002). Testing observationally the Chandrasekhar mass-radius relation continues to be a challenge. Originally in conflict with theoretical predictions, Procyon B now falls right on the carbon core relation after a proper redetermination of its effective temperature (Provencal et al. 2002). Following the spectacular discoveries of planetary systems around stars, the question of the fate of planets after the late evolutionary phases of the central stars has motivated exciting searches for planets around white dwarfs (e.g., Burleigh et al. 2002).

8. Transport Processes in Stellar Interiors

8.1. Convection, Rotational Mixing (J.-P. Zahn)

The treatment of convection continues to be one of the main weaknesses of stellar structure theory, though 3-D numerical simulations are becoming ever more realistic. Some of these simulations treat only the surface and sub-surface layers, in Cartesian geometry (e.g., Stein & Nordlund 2000; Miesch et al. 2000; Porter & Woodward 2000), and are used to calculate spectral line profiles for comparisons with observed ones (e.g., Allende Prieto et al. 2002), the flux of acoustic waves (Samadi et al. 2002), or the extent of convective penetration (Brummel et al. 2002). Others model the whole convection zone, in spherical geometry (e.g., Robinson & Chan 2001; Brun & Toomre 2002).

As these simulations are still too bulky and time consuming to be implemented in stellar evolution codes, other approaches are being explored, such as including higher-order moments, which permits a non-local treatment (e.g., Canuto 2000): actual stellar models have been constructed by Kupka & Montgomery (2002) and by Xiong & Deng (2001). But it is not yet known whether this approach is accurate enough to dispense with the 3-D simulations; in other words, whether a 1-D model is able to render the complexities of strongly stratified convection, with its sharp contrast between upflows and downflows.

The role of rotation-induced mixing has continued to be investigated, mainly using the prescriptions of Maeder and Zahn (1998). In a series of papers, Maeder & Meynet (2001, and references therein) computed the evolution of rotating stars of mass above 9 $\mathcal{M}_\odot$, and they examined the role of rotation on the nucleosynthesis of nitrogen at low metallicities (Meynet & Maeder 2002). Using somewhat different prescriptions for the rotational mixing, Heger et al. (2000) explored the pre-supernova phases. Some progress has also been achieved to explain the quasi-uniform rotation of the solar radiation zone. Garaud (2002) calculated the effect of a fossil magnetic field, showing that it could inhibit the spread of the tachocline. On the other hand, Talon et al. (2002) confirmed the possible contribution of gravity waves to the extraction of angular momentum, which could even lead to a core rotating slower than the surface. Which of these two is the most efficient process is not presently known.

8.2. Diffusive Processes (G. Michaud)

It is important to have evolutionary models with atomic diffusion, including the effects of radiative accelerations and thermal diffusion, since these are the only models that may currently be calculated from first principles, without arbitrarily suppressing transport. One may then determine how they are perturbed by macroscopic hydrodynamic processes. In Pop. I stars, it has been shown (Richard et al. 2001) that an iron peak convection zone occurs at $T \simeq 200,000$ K in all stars with $T_{\rm eff} \geq 7000$ K. It is caused mainly by Fe accumulating there, as the result of radiative accelerations from deeper in the star. They also showed that the interaction of helium diffusing outward from the convective core with inward diffusing metals, leads to semi-convective zones outside of the convective core. J. Richer et al. (2000) showed that the abundance anomalies observed on AmFm stars could be explained by diffusion occuring below that Fe convection zone, about 3 times deeper in mass, though some turbulent transport appears to be required to reduce the anomalies. Turcotte et al. (2000) demonstrated that these models are compatible with the pulsating properties of δ Scuti and δ Delphini stars.

In Pop. II stars, Richard et al. (2002) have shown that, when radiative accelerations are included in evolutionary model calculations, overabundances of many metals are produced in globular cluster turnoff stars with $T_{\rm eff} \geq 5900$K. In order to be compatible with Li observations, they suggested that turbulence has to be present to reduce the gravitational settling of Li: Salaris & Weiss (2001) have argued that this may not be necessary.

9. Helio- and Astero-Seismology (W. Dziembowski)

During the past three years, which had high and varying solar activity, research in helioseismology concentrated on the analysis and interpretation of data from instruments on board the SOHO spacecraft and from the GONG network of ground-based instruments. Perhaps the most important discovery is that torsional oscillations persist to a large depth ($\sim 0.1 R_\odot$) within the convective envelope (Antia & Basu 2000; Howe et al. 2000). Chou & Dai (2001) found significant changes in the meridional flow extending down to a similar depth. New models of the Sun's interior constrained by seismic data were produced by Bahcall et al. (2001) and by Turck-Chièze et al. (2001).

The highlight in asteroseismology was the discovery of solar-like oscillations in such distant stars as α CMi, (Martić et al. 1999), α Cen (Bouchy & Carrier 2002), and β Hyd (Bedding et al. 2001; Carrier et al. 2001). Exploitation of these data in the context of stellar interior modeling has already begun; e.g., Thévenin et al. (2002) have constructed models of the double star α Cen A,B taking into account the seismic data. In addition, the WET network continues to provide rich frequency data on rapidly varying stars — mainly on oscillating white dwarfs. Vauclair et al. (2002) identified 37 modes in the hottest white dwarf known (RXJ 2117+3412) and determined its properties: the frequency splitting pattern has revealed a depth-dependent rotation rate. Handler et al. (2002) obtained and interpreted oscillation spectrum of the DBV star CBS 114, from which they derived many of the star's properties, as well as a constraint on the ^{12}C(α, γ)^{16}O cross-section.

New challenges to stellar evolutionary theory came from Cepheid data. Beaulieu et al. (2001) pointed out problems with the M-L relation and the extent of the blue loop. Pietrukowicz (2002) showed that rates of period changes in Magellanic Cloud Cepheids are systematically much lower than predicted by current models of stars in the loop phase.

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