INSTABILITIES IN LUMINOUS EARLY TYPE STARS

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PROCEEDINGS OF A WORKSHOP
IN HONOUR OF PROFESSOR CEES DE JAGER
ON THE OCCASION OF HIS 65TH BIRTHDAY
HELD IN LUNTEREN, THE NETHERLANDS, 21–24 APRIL 1986

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PUBLISHER'S NOTE

We herewith take the opportunity to express our sincere gratitude and admiration to Cees de Jager who for many years has been the driving force and architect of the Reidel Astronomy programme.

Since the early sixties Cees de Jager has invested a lot of time and energy in this programme and has advised the company on directions to go and indicated gaps in the literature that needed to be filled. This was all done for the sole motive of serving the field of Astronomy.

It is no exaggeration to state that his activities have resulted in a great many publications that have enriched the literature and stimulated research in this exciting field.

Although officially retired, Cees seems now to be busier than ever. We hope that our association will last for many more years. All of us at Reidel wish Cees de Jager a happy and active retirement.

J. F. Hattink

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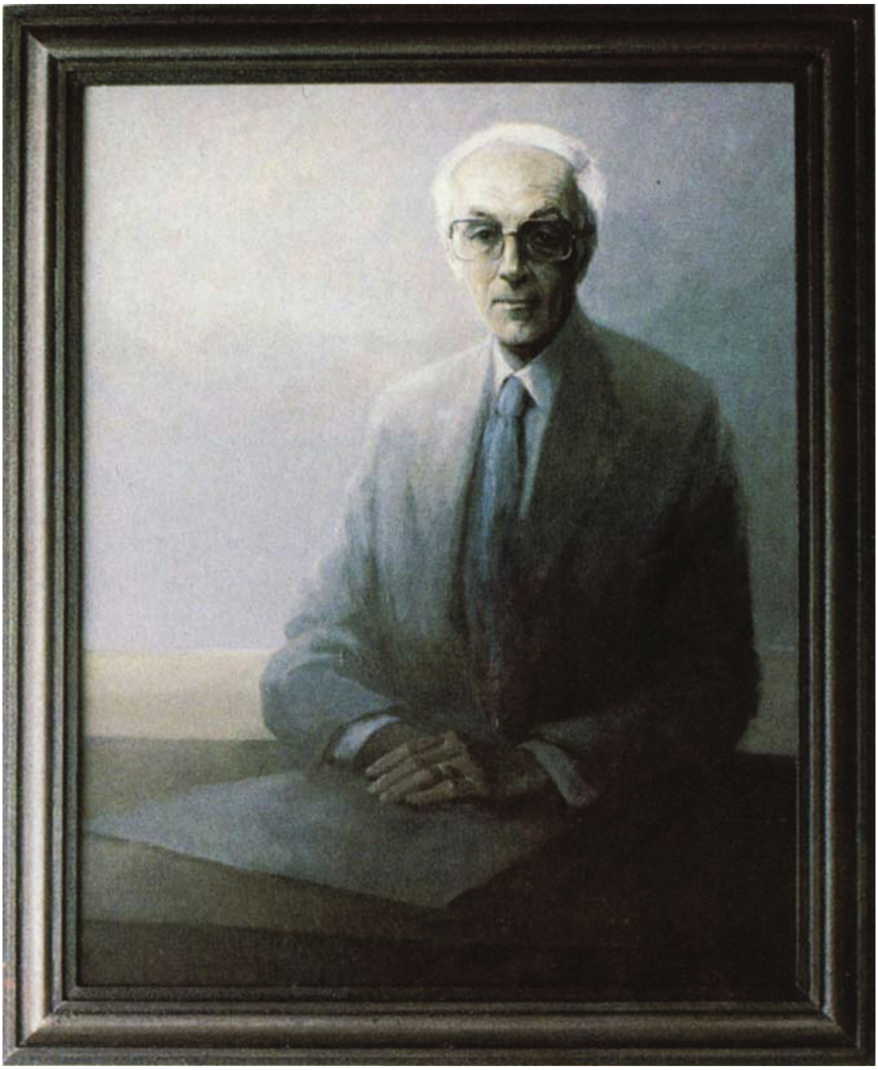

PREFACE

On April 28 1986 Cornelis de Jager reached the age of 65 years. On April 30 he officially retired from the University of Utrecht where he has held a Chair for Stellar Astrophysics, later changed into Space Physics, since 1958.

Cees de Jager, as he prefers to be called by his friends, has had an active and successful life in science. His interest in astronomy was raised by his father under the clear skies of Celebes (Indonesia). He started a study in physics and astronomy as a student of the late M. Minnaert in Utrecht during World War II. When in 1943 the occupying forces recruited students who did not want to sign the declaration of loyalty for their war-efforts, Cees and three fellow students went into hiding at the Observatory in Utrecht. During this very "quiet" period van de Hulst developed the theory of the 21 cm radiation of neutral hydrogen and de Jager started the observations of variable stars in the pitch dark nights of a country at war. The study of Beta Cepheids rapidly awoke his interest which was kept throughout the years. In 1958 he organized an international campaign to observe 12 Lac spectroscopically and photometrically, which was a great success.

His main interest was initially directed at the Sun. After a thesis on "The Hydrogen Lines in the Solar Spectrum" he wrote an extensive review article on solar physics for Handbuch der Physik. When the first opportunities for observations from rockets above the earth atmosphere became available in the early sixties, he realized their importance for solar and stellar research and started to develop rocket X-ray instruments. This led to the foundation of the Laboratory for Space Research in Utrecht in 1961 of which he became the first director. At about the same time (1963) he succeeded Minnaert as a director of the Observatory. Later (1968) he founded the Astrophysical Institute in Brussels.

De Jager is an excellent organizer. With a clear vision of the important role of astronomy for the development of science and with a keen eye for technical possibilities on one hand and a broad insight in astrophysical problems on the other, he has played an important role in many international scientific organizations: ESRO (now ESA), IAU (General Secretary from 1970 to 1973), COSPAR (President from 1972 to 1978 and from 1982 to 1986), ICSU (President from 1978 to 1980) and many others. His affable and honest character combined with his tenacity in defending his ideas has made him a successful advocate for international astronomy.

Cees de Jager is one of the rare astronomers who reach a second youth in their scientific career after the age of 50. After 1977, when his burden of directorates was lightened, he enthusiastically returned to research in particular to his lifelong pet-subject: stellar instabilities. With a group of colleagues he discovered the phenomenon of "shock-driven mass loss" from ß Ceph stars. He also started a very ambitious project to write a book about "The Brightest Stars" which was published by Reidel in 1980. Since then he is full time studying the hypergiants in order to understand the processes in their teneous atmospheres and their variability. His investigations of the motions in these atmospheres led him to the suggestion that turbulence sets an upperlimit to the luminosity of very bright stars. This predicted turbulent upperlimit is now called the "de Jager limit". His large room at the Laboratory for Space Research is always a center of activity where he is surrounded by five or six students each one studying one of his pet hypergiants. He shows no sign of diminishing interest or curiosity for stellar instability.

The first ideas for a meeting in honour of Cees de Jager was born in 1984 at a meeting of the Dutch Studygroup of Extended Stellar Atmospheres (SUA). A preliminary organizing committee, consisting of A. van Genderen, H. Lamers and P.S. Thé, was formed. Very early on it was decided to choose the subject of "Instabilities in Luminous Early Type Stars" because that was the main interest of de Jager in recent years. Moreover it was felt that the meeting should be shaped as a "workshop" with a small number of invited participants, in order to stress the ongoing interest and active research of de Jager in this field.

The Scientific Organizing Committee, consisting of I. Appenzeller (Heidelberg), P. Conti (Boulder), R. Humphreys (Utrecht), C. de Loore (Brussels), H. Lamers (Utrecht, chairman), P.S. Thé (Amsterdam), and A. van Genderen (Leiden), met at the IAU Symposium nr 116 in Greece in May 1985 and shaped the scientific program, suggested invited review speakers as well as participants to be invited. The format of the meeting consisted of 12 sessions of a review and an extended general discussion. New results could be presented in posters and mentioned in the general discussion. This format turned out to be very successful in generating lively discussions between theoreticians and observers. This led a worried observer to ask: "Did we make the wrong observations?" and an impatient theoretician exclaim "You observers should have more patience!". The discussions are included in these proceedings.

The Local Organizing Committee consisting of K. van der Hucht (chairman) and J. Vogel has done an excellent job in selecting the very nice accommodation of "De Blije Werelt" located in the woods of Lunteren, and smoothly and efficiently running the local organization including a 20 mile bicycle trip through the woods of the National Park to the van Gogh paintings in the Kröller-Müller museum. The LOC was supported at the workshop by the students J. Coté, P. Mulder, A. Pieters and J. Wollaert. The discussions were recorded by means of hand-out forms by R. Waters.

We like to thank all those organizations who contributed generously, either financially or otherwise. In particular we acknowledge financial contributions from: SRON Space Research Laboratory in Utrecht; Sonnenborgh Observatory in Utrecht; the University of Utrecht; the Dutch Royal Academy of Sciences; the Leids Kerkhoven Bosscha Fonds; COSPAR; ESA and Fokker.

We are grateful to the Reidel Publishing Company, in particular G.

Kiers, for the publication of these proceedings with a colour portrait of Cees de Jager. This portrait was painted by W.C. van de Hulst, a brother of the astronomer, and presented on the occasion of Cees' retirement. The discussions were skilfully typed by Louise Cramer and Celia Roovers. The photographs were taken by H. Nieuwenhuijzen.

Most of all we want to thank all the participants for their contributions. The main goal of this workshop has certainly been achieved: "To teach Cees de Jager many new and fascinating facts about instabilities in luminous early type stars, which will be useful for him in his ongoing scientific career."

The participants in front of the Conference Center
"De Blije Werelt" ("the happy world") in Lunteren.

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Section I

Invited Reviews and General Discussions

The final meeting of the Scientific Organizing Committee on the evening before the workshop. Peter Conti, Immo Appenzeller, Arnoud van Genderen, Bert de Loore, Pik-Sin Thé, Roberta Humphreys, Henny Lamers and Cees de Jager (consultant).

THE UPPER HR DIAGRAM - AN OBSERVATIONAL OVERVIEW

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The most massive and most luminous stars have always intrigued astronomers with considerable speculation about the upper limits to stellar masses and luminosities. Only about 20 years ago the nominal upper limit to stellar masses was supposed to be about 60 $M_\odot$ (Ledoux 1941, Schwarzschild and Harm 1959) due to vibrational instability. In a more massive star the pulsation amplitude was expected to grow until its outer layers were ejected reducing the mass or even destroying the star. Theory seemed to preclude the existence of very massive stars. But a few stars appeared to be very massive such as Plaskett's star, and the brightest supergiants in the Large and Small Magellanic Clouds observed by Feast et al. (1960). They found that many stars in the Clouds have visual luminosities that require masses close to 100 $M_\odot$. And by 1970, η Car (Davidson 1971) had been recognized as a very massive star. At about the same time, theorists (Appenzeller 1970, Ziebarth 1970) found that the vibrational instability was limited and the upper mass limit was closer to 100 $M_\odot$. Non-catastrophic mass loss might occur but massive stars were theoretically possible.

During the past decade or so, both the observational and theoretical studies of massive stars and their evolution have progressed very rapidly and in new directions. Observationally, this development was spurred by 1) the recognition of the importance of mass loss in stars >20 or 30 $M_\odot$ across the entire HR diagram thanks largely to results from IUE and infrared observations (see reviews by Hutchings 1978, Barlow 1978), 2) modern discussions of the HR diagrams for the luminous stars in our Galaxy and the Magellanic Clouds (Humphreys 1978, Humphreys and Davidson 1979), plus observations of the brightest and most massive stars in other nearby galaxies, and 3) the addition of mass loss and internal mixing which produced physically more realistic models and better agreement with the observations (see recent review by Chiosi and Maeder 1986).

The observed upper HR diagram and the characteristics of some of its most luminous stars provided the empirical evidence for an upper luminosity boundary likely determined by the relative stability or instability of the photospheres of the evolved most massive stars. The observed HR diagram for massive stars for our solar neighborhood and

H. J. G. L. M. Lamers and C. W. H. de Loore (eds.), Instabilities in Luminous Early Type Stars, 3–22.

other nearby galaxies is the basis for our current scenarios of massive star evolution and for much of the motivation behind our interest in the role of instabilities on their evolution.

In this opening paper I will review the upper HR diagram and the observational uncertainties in its determination. I will also discuss the upper luminosity boundary defined by the most luminous hot and cool stars, and the observational evidence for high mass loss rates and instabilities in these stars' atmospheres.

1. THE OBSERVED HR DIAGRAM - ITS DERIVATION AND UNCERTAINTIES

The HR diagram is normally plotted in one of two ways; M_V versus spectral type or color and M_{Bol} versus log T_{eff}. The first is based only on observed parameters while the second depends on calibrations to produce a diagram for comparison with the theoretical models and evolutionary tracks.

We rely very heavily on these HR diagrams and the locations on the HRD of different groups of stars for our understanding of massive star evolution and the role of atmospheric instabilities and resulting mass loss on that evolution. Before discussing the main features of the HRD and their implications I will briefly summarize the calibrations and uncertainties on which it depends.

1.1. Observed Parameters - Spectral Type and Photometry

There are of course personal errors in classification which are difficult to assess, but my comparisons of published types suggest that an uncertainty of $\pm$ half a type and $\pm$ half a luminosity class are typical; among the supergiants this is usually at most the difference between Ia and Iab for example. The errors in the photometry, at least for stars in our galaxy and the Magellanic Clouds, is usually quite small. The effective temperature and bolometric correction depends on the spectral type, but its uncertainties are <10% and are small compared to differences among the different effective temperature and bolometric correction scales.

1.2. Calibrated Parameters

The determination of effective temperatures for most hot stars and supergiants depends mostly on an analysis of the absorption line spectrum plus a model atmosphere with some empirical data from energy distributions and angular diameters. For the hot stars there have basically been two temperature scales, the 'hot' scale advocated by Conti (1973) based on non-LTE models by Auer and Mihalas (1972) and the 'cool' scale proposed by Underhill (1980, 1983) based on the stellar continua. The hot scale has been modified downwards somewhat by the recent non-LTE analysis by Kudritzki and his collaborators (Kudritzki 1980, Kudritzki et al. 1983, Simon et al. 1983). The now modified hot scale has in my opinion consensus support and is based on a firm foundation in stellar atmospheres. Use of the cool scale (see review by Böhm-Vitense 1981) produces an HR diagram in which the hottest stars are shifted to lower temperatures and luminosities leaving a large gap near the upper main sequence which must be explained; for example, by supposing most of the O-type stars must be hidden (see Garmany et al. 1982).

The fundamental data on effective temperature for stars later than A-type is also based on model atmospheres. There is less uncertainty about their calibration. The temperature scale for the cool supergiants, types K and M, is now much better determined with increased use of infrared data (see Lee 1970, Ridgway et al. 1980).

With increased ultraviolet and infrared observations the energy distributions and thus total luminosities of many more stars are available. The bolometric corrections (B.C.) for hot stars largely depend on the adopted effective temperature scale, thus uncertainties in the temperatures propagate to the bolometric corrections. The bolometric corrections for the evolved intermediate type supergiants are small and any uncertainties do not cause large changes in M_{Bol}. Bolometric luminosities for the red supergiants are large and for a long time were considered very uncertain, but again the infrared observations have greatly improved the accuracy of their bolometric corrections (see Elias, Frogel and Humphreys 1985). Indeed, given that a star is an M supergiant, the bolometric correction and the bolometric luminosity is known to an accuracy of ± 0.1 mag. With JHK photometry the luminosities of the red supergiants are now very well defined.

These are the fundamental calibrations required to produce the M_{Bol} versus log T_{eff} diagram; however, there are additional sources of errors that arise from the need to correct the data for interstellar extinction and to derive the absolute luminosities from a distance. Although there is evidence for variations in the IS extinction law in the ultraviolet in our galaxy and others, most of the available data supports a nearly uniform extinction law in the blue-visual to near infrared wavelength region.

The intrinsic color data for stars of all types have been summarized by many investigators (Johnson 1966, FitzGerald 1970, Schmidt-Kaler 1983). In a recent paper, Conti et al. (1986) have questioned the previously published U-B colors for the O-stars, based on their observations in the LMC. For both the blue and intermediate-type luminous stars, though, the extinction corrections are usually based on the (B-V) colors and for the red supergiant the infrared observations allow us to determine their luminosities at a wavelength where extinction can be essentially ignored.

The distance is perhaps the single most important pice of information in determining the HR diagram for luminous stars. Nearly all of these stars are too distant for direct measurement of their distances and thus their luminosities. In our galaxy, their visual and bolometric absolute luminosities are derived from membership in clusters and associations with known distances (e.g., Humphreys 1978, Humphreys and McElroy 1984). A fundamental reference for this procedure is Blaauw (1965). Walborn (1972, 1973) has provided a revised calibration for O and early B-type stars, and recent summaries by Schmidt-Kaler (1983) and Humphreys and McElroy (1984) give luminosity calibrations for larger data sets. These calibrations typically have a standard deviation of