

Instabilities in Luminous Early Type Stars

**H. J. G. L. M. Lamers
C. W. H. de Loore**
(editors)



**Astrophysics and
Space
Science
Library**

D. Reidel Publishing Company

INSTABILITIES IN LUMINOUS EARLY TYPE STARS

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

Edited by

HENNY J. G. L. M. LAMERS

*Sonnenborgh Observatory and SRON Laboratory for Space Research,
Utrecht, The Netherlands*

and

CAMIEL W. H. DE LOORE

*Astrophysical Institute, Vrije Universiteit Brussel and
Rijksuniversitair Centrum Antwerpen,
University of Antwerp, Belgium*

D. REIDEL PUBLISHING COMPANY

A MEMBER OF THE KLUWER  ACADEMIC PUBLISHERS GROUP

DORDRECHT / BOSTON / LANCASTER / TOKYO

Instabilities in luminous early type stars.

(Astrophysics and space science library; v. 136)

Includes indexes.

1. Shell stars—Congresses. 2. Wolf-Rayet stars—Congresses. 3. Jager, C. de (Cornelis de), 1921– . I. Jager, C. de (Cornelis de), 1921– . II. Lamers, Henny J. G. L. M., 1941– . III. Loore, Camiel W. H. de. IV. Series.
QB843.S53I57 1987 523.8 87-9664
ISBN 90-277-2522-5

Published by D. Reidel Publishing Company,
P.O. Box 17, 3300 AA Dordrecht, Holland.

Sold and distributed in the U.S.A. and Canada
by Kluwer Academic Publishers,
101 Philip Drive, Assinippi Park, Norwell, MA 02061, U.S.A.

In all other countries, sold and distributed
by Kluwer Academic Publishers Group,
P.O. Box 322, 3300 AH Dordrecht, Holland.

All Rights Reserved

© 1987 by D. Reidel Publishing Company, Dordrecht, Holland

No part of the material protected by this copyright notice may be reproduced or
utilized in any form or by any means, electronic or mechanical
including photocopying, recording or by any information storage and
retrieval system, without written permission from the copyright owner

Printed in The Netherlands

PUBLISHER'S NOTE

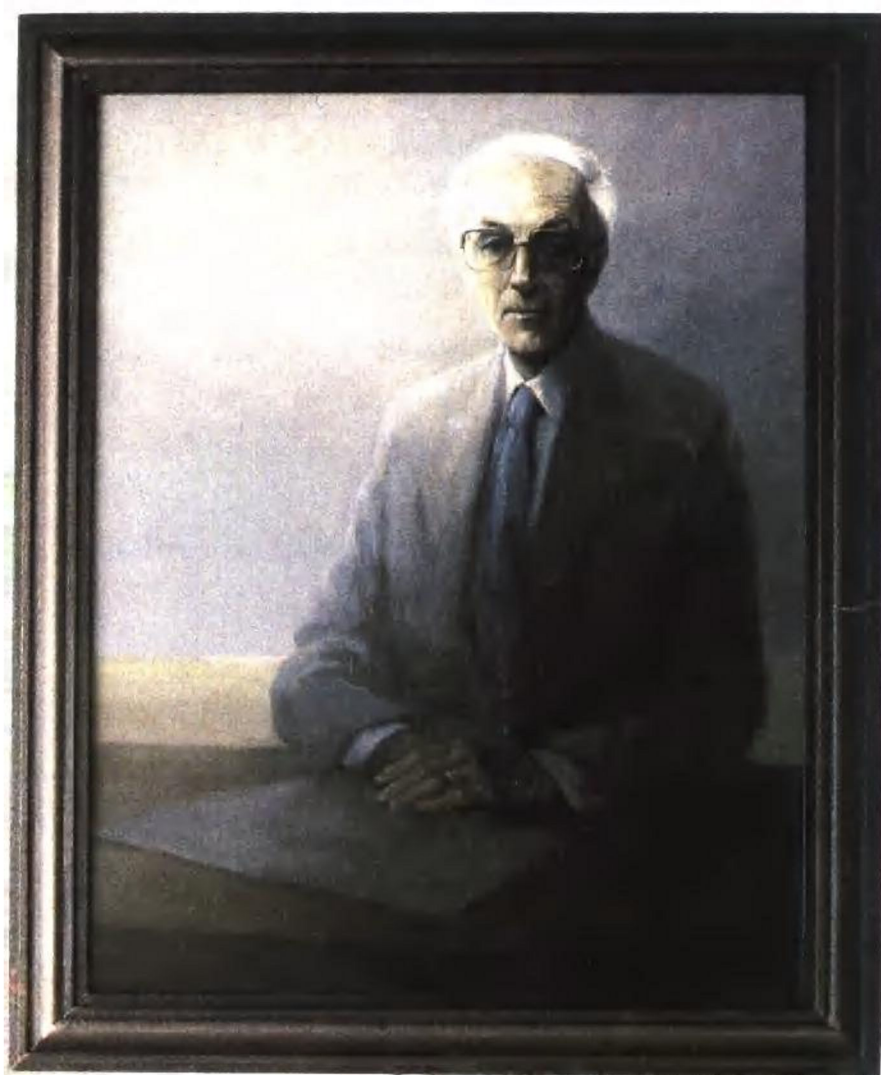
We herewith take the opportunity to express our sincere gratitude and admiration to Cees de Jager who for many years has been the driving force and architect of the Reidel Astronomy programme.

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



x

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 instabil-

ities. With a group of colleagues he discovered the phenomenon of "shock-driven mass loss" from β 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 Blijе Werelt" ("the happy world") in Lunteren.

LIST OF PARTICIPANTS

- I. Appenzeller, Landessternwarte, Königstuhl, Heidelberg,
B.R. Deutschland.
- D. Baade, ST-ECF, ESO, Garching bei München, B.R. Deutschland.
- L. Bianchi, Osservatorio Astronomico di Tirone, PINO TORINESE
(TO), Italia.
- R. Bonnet, ESA Headquarters, Paris, France.
- G. Burki, Observatoire de Genève, Sauverny, Suisse.
- A. Cassatella, ESA-IUE Tracking Station, Villafranca del
Castillo, Madrid, Spain.
- J. Cassinelli, Astronomy Dept., University of Wisconsin, Madison
WI 53706, U.S.A.
- J. Castor, L.Livermore Natl. Lab., University of California,
Livermore, CA, U.S.A.
- P. Conti, JILA, University of Colorado, Boulder, CO, U.S.A.
- J. Côté, SRON, Ruimteonderzoek Utrecht, Utrecht, Nederland.
- K. Davidson, Dept. of Astronomy, Univ. of Minnesota, Minneapolis,
U.S.A.
- D. Dawanas, ITB Observatorium Bosscha, Lembang, Jawa Barat,
Indonesia.
- J.-P. De Cuyper, Etterbeek, België.
- A. van Genderen, Sterrewacht Leiden, Leiden, Nederland.
- T. de Graauw, SRON Ruimteonderzoek Groningen, Groningen, Nederland.
- A. Greve, IRAM, Université de Grenoble, St-Martin-d'Heres, France.
- M. de Groot, Armagh Observatory, Armagh, Northern, Ireland, U.K.
- G. Habets, Sterrenkundig Instituut Anton Pannekoek, Amsterdam,
Nederland.
- G. Hammerschlag, Sterrenkundig Instituut Anton Pannekoek, Amsterdam,
Nederland.
- A. Hearn, Sterrewacht Sonnenborgh, Utrecht, Nederland.
- H. Henrichs, JILA, University of Colorado, Boulder, CO, U.S.A.
- E. van den Heuvel, Sterrenkundig Instituut Anton Pannekoek, Amsterdam,
Nederland.
- L. Houziaux, Institut d'Astrophysique, Université de Liège,
Cointe-Ougrée, Belgique.
- K. van der Hucht, SRON Ruimteonderzoek Utrecht, Utrecht, Nederland.
- R. Humphreys, Dept. of Astronomy, Univ. of Minnesota, Minneapolis,
MN, U.S.A.
- C. de Jager, Sterrewacht Sonnenborgh and SRON-ROU, Utrecht,
Nederland.
- M. Jerzykiewicz, Astronomical Institute, Wroclaw, Poland.
- P. Korevaar, Sterrewacht Sonnenborgh, Utrecht, Nederland.
- H. Lamers, Sterrewacht Sonnenborgh and SRON-ROU, Utrecht, Nederland.
- C. Leitherer, Landessternwarte, Königstuhl, Heidelberg, B.R. Deutschland.
- C. de Loore, Astrofysisch Instituut, VUB, Brussel, België
- A. Maeder, Observatoire de Genève, Sauverny, Suisse
- A. Moffat, Départ. de Physique, Univ. de Montréal, Montréal, Canada.
- P. Mulder, SRON Ruimteonderzoek Utrecht, Utrecht, Nederland.
- E. Müller, Basel, Suisse.
- H. Nieuwenhuijzen, Sterrewacht Sonnenborgh, Utrecht, Nederland.
- A. Noels, Institut d'Astrophysique, Univ. de Liège, Cointe-Ougrée,
Belgique.
- Y. Osaki, Department of Astronomy, Univ. of Tokyo, Tokyo, Japan.

- S. Owocki, Center for Astrophys. and Space Science, UC San Diego,
La Jolla, CA, U.S.A.
- A. Pijpers, SRON Ruimteonderzoek Utrecht, Utrecht, Nederland.
- F. Praderie, Observatoire de Meudon, Meudon, France.
- M. Raharto, Sterrewacht Leiden, Leiden, Nederland.
- J. Rountree-Lesh, Bethesda, MD, U.S.A.
- G. Rufener, Observatoire de Genève, Sauverny, Suisse.
- G. Rybicki, Harvard-Smithsonian Center for Astrophysics, Cambridge,
MA, U.S.A.
- R. Schulte-Ladbeck, Landessternwarte, Königstuhl, Heidelberg,
B.R. Deutschland.
- L. Smith, Dept. of Physics and Astronomy, UCL, London, U.K.
- J. Smolinski, Centrum Astronomiczne im M. Kopernika, Torun, Poland.
- O. Stahl, European Southern Observatory, Garching bei München,
B.R. Deutschland.
- D. Stickland, Rutherford Appleton Laboratory, SAD, Chilton, Didcot,
U.K.
- P. Thé, Sterrenkundig Instituut Anton Pannekoek, Amsterdam, Nederland.
- H. Tjin A Djie, Sterrenkundig Instituut Anton Pannekoek, Amsterdam,
Nederland.
- P. Ulmschneider, Institut für Theor. Astrophys. Heidelberg,
B.R. Deutschland.
- R. Viotti, Istituto Astrofisica Spaziale CNR, Frascati, Italia.
- J.-M. Vreux, Institut d'Astrophysique, Univ. de Liège, Sart Tilman, Belgique.
- C. Waelkens, Astronomisch Instituut, Univ. van Leuven, Heverlee,
België.
- W. Wamsteker, ESA-IUE Observatory VILSPA, Madrid, Spain.
- L. Waters, SRON Ruimteonderzoek Utrecht, Utrecht, Nederland.
- P. Wesselius, SRON Ruimteonderzoek Groningen, Groningen, Nederland.
- P. Williams, The Royal Observatory, Edinburgh, Schotland, U.K.
- A. Willis, Dept. of Physics and Astronomy, UCL, London, U.K.
- H. van Woerden, Kapteyn Laboratorium, Groningen, Nederland.
- B. Wolf, Landessternwarte, Königstuhl, Heidelberg, B.R. Deutschland.
- J. Wollaert, SRON Ruimteonderzoek Utrecht, Utrecht, Nederland.
- J.-P. Zahn, Observatoire de Toulouse, Toulouse, France.

TABLE OF CONTENTS

Frontispiece: Cornelis de Jager: a painting by W. C. van de Hulst	x
Preface	xi
Group Photograph	xiv
List of Participants	xv

SECTION I: INVITED REVIEWS AND GENERAL DISCUSSIONS

The upper HR diagram – An observational overview	3
R. M. Humphreys	
Discussion	16
Observations and interpretations of stellar pulsations	23
G. Burki	
Discussion	34
Theory of non-radial pulsations in massive early-type stars	39
Y. Osaki	
Discussion	48
Theory of vibrational instabilities in luminous early type stars	55
I. Appenzeller	
Discussion	68
Observed variations in O and Of stars	73
D. Baade	
Discussion	75
Observed variations in Wolf-Rayet stars	81
J. M. Vreux	
Discussion	93
Variations in luminous blue variables	99
H. J. G. L. M. Lamers	
Discussion	119

Giant outbursts of the Eta Carinae - P Cygni type	127
K. Davidson	
Discussion	136
Instabilities due to convection and rotation	143
J.-P. Zahn	
Discussion	154
Shock waves in luminous early-type stars	159
J. I. Castor	
Discussion	171
Radiation driven instabilities	175
G. B. Rybicki	
Discussion	185
Stellar instabilities in the upper part of the Hertzsprung-Russell Diagram	191
C. de Jager	

SECTION II: POSTER PAPERS

Massive stars in nearby galaxies	201
P. Massey, J. Hutchings and L. Bianchi	
Rate of mass-loss in the Hertzsprung-Russell Diagram	205
C. de Jager, H. Nieuwenhuijzen and K. A. van der Hucht	
The unstable of 06.5f?p star HD 148937 and its interstellar environment	209
C. Leitherer and C. Chavarria-K.	
Two comments of the Beta Cephei variable 12 Lacertae	211
M. Jerzykiewicz	
Non radially pulsating Wolf-Rayet stars	213
A. Noels and R. Scuflaire	
Sobolev type line profile in case of non radial wind density perturbations	217
R. Scuflaire and J. M. Vreux	
Episodic distortion and dust formation in the wind of WR140	221
P. M. Williams, K. A. van der Hucht, H. van der Woerd, W. M. Wamsteker, T. R. Geballe, C. D. Garmany and A. M. T. Pollock	

Photometric variability of Wolf-Rayet stars A. F. J. Moffat, M. M. Shara and R. Lamontagne	227
Improved mass loss rates for WC7-9 stars: their effect on the Wolf-Rayet stellar wind momentum problem J. P. Cassinelli and K. A. van der Hucht	231
Variability of Wolf-Rayet stars in linear polarization A. F. J. Moffat, P. Bastien, L. Drissen, N. St-Louis and C. Robert	237
An extended nebulosity surrounding the S Dor variable R127 I. Appenzeller, B. Wolf and O. Stahl	241
The LMC-S Dor variable R 71 - an IRAS point source B. Wolf and F.-J. Zickgraf	245
Eclipse spectrum of the LMC P Cyg star R 81 O. Stahl, B. Wolf and F.-J. Zickgraf	249
The light- and colour variation of Eta Carinae for the years 1983–1986 in the VBLUW system A. M. van Genderen and P. S. Thé	253
Do superluminous stars really explode? R. Viotti	257
Radiation pressure in acoustic wave calculations of early type stars B. E. Wolf and P. Ulmschneider	263
The influence of photospheric turbulence on stellar mass loss C. de Jager and H. Nieuwenhuijzen	267
Nonlinear dynamics of instabilities in line-driven stellar winds S. P. Owocki, J. I. Castor and G. B. Rybicki	269
The X-ray emission of Tau Sco, Bo V, and the problems posed for embedded shock models J. P. Cassinelli	273
Name index	279
Object index	287

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

ROBERTA M. HUMPHREYS
University of Minnesota
Department of Astronomy
116 Church Street, S.E.
Minneapolis, MN 55455

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