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Gravitational Collapse: from massive stars to planets (© Copyright 2004: IA, UNAM)
Editors: G. García-Segura, G. Tenorio-Tagle, J. Franco, & H. W. Yorke

OUTBURSTING STARS, PRE-MAIN-SEQUENCE STELLAR EVOLUTION, CONVECTION, AND LITHIUM BURNING

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RESUMEN

Esta nota histórica resume algunos de los eventos clave relacionados con la evolución pre-secuencia principal y en particular, a la importancia del transporte convectivo de energía, que llevó a mi disertación doctoral en 1965.

ABSTRACT

This historical note summarizes some of the key events related to pre-main-sequence evolution, and in particular the importance of convective energy transport, that led to my Ph. D. dissertation in 1965.

Key Words: **CONVECTION — PLANETS AND SATELLITES: FORMATION — STARS: EVOLUTION — STARS: PRE-MAIN-SEQUENCE**

1. 1937

In my birth year, a star in Orion, known as FU Orionis, brightened unexpectedly by about 6 magnitudes in visual light. Unlike novae and supernovae, which fade relatively quickly after maximum light, this object has stayed at almost constant brightness ever since that time, more than 66 years ago. It was known to be a young star, and it was later deduced (Herbig 1977) that all young stars go through such outbursts, probably more than once. The actual cause of the outburst is still a matter of debate. Most theorists subscribe to the view that the event had its origin through a thermal instability in a disk around the star which results in a transient enhanced phase of accretion of matter from the disk onto the star (reviewed by Hartmann, Kenyon, & Hartigan 1993). In fact theorists believe in this solution so strongly that they have essentially stopped working on the problem. However the dissenters (Herbig, Petrov, & Duemmler 2003) use high resolution spectroscopy to say that there is very little observational evidence for a disk, and that one could equally well explain the outburst by a brightening of the star itself. A mechanism for such brightening could be an instability in a convective, rotating star which would result in a bar-like deformation, leading to heating and expansion of the outer layers of the star and some mass loss (Larson 1980). Whether correct or not, this argument highlights the importance of convective energy transport in the early evolution of stars.

2. 1952

In this year I started high school in Salt Lake City, Utah. At the time, just a few blocks away at the University of Utah Department of Physics, Dr. Eugene Parker was working on the theory of turbulence and convection in the outer layers of the Sun, a topic that was to be of great importance to me later on in connection with stellar evolution. In the abstract of a paper given at an American Astronomical Society meeting, “ An analytical investigation of turbulence and acoustics in the solar ionization zone” (Parker 1952), he derives turbulent velocities of 0.6 km/s, in agreement with observations, and disputes the claim by Martin Schwarzschild (1947), (who was later to become my postdoc advisor), that the acoustic radiation from the turbulent velocity field is adequate to heat the solar corona. Parker, of course, later moved to the University of Chicago and became one of the pioneers in the development of the theory of stellar winds and of astrophysical magnetic fields.

3. 1955

I graduated from high school. In this year Louis Henyey, who was later to become my thesis advisor, and colleagues (1955) published the first electronically calculated pre-main-sequence evolutionary tracks, using the Henyey method. The tracks in the Hertzsprung–Russell diagram, calculated for a range of masses from 0.65 $M_\odot$ to 2.29 $M_\odot$, included nuclear reactions and were carried to the age-zero main sequence, but they did not include the effects of a surface convection zone. They became known as “radiative tracks”, or “Henyey tracks”. Henyey was aware that surface convection zones develop in stars

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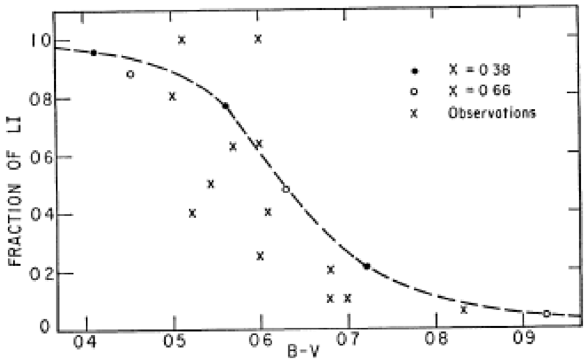

Fig. 1. The fraction of original total lithium remaining in the convective envelope for contracting models of various masses that have reached the main sequence, plotted against arrival position on the main sequence in terms of $B-V$. The calculations were done with a Henyey stellar evolution code. *Open circles:* calculations with hydrogen mass fraction $X = 0.66$. *Filled circles:* calculations with hydrogen mass fraction of 0.38. *Crosses:* lithium observations in the Hyades cluster. Reproduced by permission from Bodenheimer (1965). ©1965, University of Chicago.

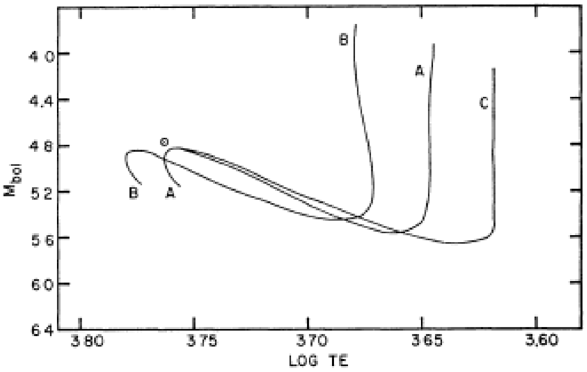

Fig. 2. Pre-main-sequence evolutionary tracks, plotted as a function of effective temperature and absolute bolometric magnitude, for 1 $M_{\odot}$, with solar composition $X = 0.66, Z = 0.0264$. Curves A and B were calculated with a ratio of convective mixing length to pressure scale height of 1.0 and 1.5, respectively. Curve C was calculated with that ratio set to 1.0 and with increased opacity in the outer layers of the atmosphere. The present Sun is indicated by the appropriate symbol. Reproduced by permission from Bodenheimer (1966). ©1966, University of Chicago.

with effective temperatures less than about 7000 K, which included the major portion of his tracks; however he did not include them because he considered the then current convection theory to be too approximate. His calculation was done on a UNIVAC, one of the very first commercial computers, a machine with a memory of 1000 72-bit words and no floating-point hardware, a size of about a one-car garage, not including the tape units, a weight of 29,000 pounds, a power consumption of about 125 kilowatts, and a cost of about one million dollars.

4. 1959

I graduated from Harvard College with a degree in Physics. Astrophysics was just starting to move into space. For example, Martin Schwarzschild (1959) and collaborators successfully launched an unmanned balloon which carried a 30-cm telescope known as Stratoscope I. From an altitude of 27 km it was able to take photographs, with a spatial resolution of 0.4 arc seconds, of the solar granulation and thus study the solar convection patterns. The first satellite observatory (an Orbiting Solar Observatory) was to be launched in 1962.

5. 1961

In this year I started astrophysical research in the Astronomy Department at the University of California, Berkeley. A major event in stellar evolution occurred when Chushiro Hayashi (1961) published the first version of his famous pre-main-sequence evolutionary tracks. They included the surface convection zone, and for a given mass, the evolutionary path was almost vertically downward in the Hertzsprung-Russell diagram, at effective temperatures ranging from 3500 K to 5000 K, increasing with increasing mass. When the vertical Hayashi track met the corresponding nearly horizontal Henyey track, it was assumed to switch over. An important prediction was that stars should not exist in equilibrium at effective temperatures cooler than that of their Hayashi track, a prediction that is consistent with observations. About this time I started working as an assistant to Louis Henyey. He didn't believe that the Hayashi tracks were correct, partly because, again, he didn't think that the theory of convection was very good, and partly because Hayashi had made a number of approximations. One of my jobs as a graduate student was to use the Henyey stellar evolution code (Henyey, Forbes, & Gould 1964), which was much more elaborate than Hayashi's method and which did by this time include surface convection, and show whether or not in fact the Hayashi tracks existed.

6. 1965

In this year I received my Ph. D. degree at Berkeley. 1965 was a great year in Astrophysics. Penzias and Wilson discovered the microwave background radiation. Neugebauer, Martz, and Leighton

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as well as Mendoza made the first observations of infrared stars. Astrophysical masers were discovered by Weaver, Williams, Dieter, and Lum. Mariner 4 flew by Mars and took the first close-up photographs of its surface. My own contribution was somewhat more modest, but still enduring. The most significant result from the thesis is shown in Figure 1. The calculations of the nuclear burning of the light element lithium in the interiors of pre-main-sequence stars, coupling with the convective mixing to the surface, were found to be in rough agreement with the observations of lithium in main-sequence stars as a function of effective temperature. In the lower-mass stars the temperature at the base of the convection zone reaches higher values and results in more surface lithium destruction than in higher mass stars. Qualitatively, that result still holds. Whether the theoretical and observational results shown in Figure 1 actually are in agreement is open to question, because of large uncertainties in both theoretical and observational quantities. Later, more accurate observations showed that the depletion in the Hyades is greater, at a given value of $B-V$, than the pre-main-sequence calculations show, a result that is still consistent with Figure 1. The extra depletion during the main sequence is a result of long-term mixing processes, still not very well understood. The calculations for hydrogen mass fraction of 0.38 were carried out because at the time the distance to the Hyades was not accurately known, and there was a discrepancy between the observational and theoretical mass-luminosity relation. This calculation was the first detailed comparison of lithium observations with theory; later it turned out that lithium is an important tracer in several different phases of stellar evolution.

The lithium calculations gave a strong indication that convective mixing is an important effect during pre-main-sequence evolution and therefore that the Hayashi tracks are correct. My calculations with Henyey's code gave evolutionary tracks that were qualitatively very similar to those of Hayashi. The code had a surface boundary condition, essentially a model atmosphere calculation, that included the mixing-length theory of convection (Böhm–Vitense 1958) with the ratio of mixing length to pressure scale height as a parameter. A calculation for 1 $M_\odot$ is shown in Figure 2. The evolution follows nearly vertical Hayashi tracks in the Hertzsprung-Russell diagram, then switches over to the more nearly horizontal Henyey tracks, where radiation transfer dominates. The uncertainties in convection theory and other parameters in the atmospheres of cool stars do not affect the nearly vertical character of the Hayashi tracks; changes in those parameters simply shift the tracks to hotter or cooler effective temperatures. The thesis calculations also showed that the existence of the Hayashi track does not depend on the initial condition assumed in the evolutionary calculation.

7. POST-THESIS NOTE

In the years following the publication of my thesis research I worked on quite a variety of topics, but one paper in particular provides a link to the work I am doing now, on formation and evolution of giant planets in the solar system and in extrasolar systems. The paper, "Calculations of the Early Evolution of Jupiter" (Bodenheimer 1974), was based on the assumption that a jupiter-mass subcondensation formed at 5 AU in the primitive solar nebula at an early stage, by gravitational instability (Kuiper 1951). In contrast, my present work is based on the alternative hypothesis, that solid cores of giant planets are built up by accumulation of small dust particles, then, when the core has obtained a mass of roughly 10 $M_\oplus$, the gas is captured from the nebula. The 1974 calculation started with a planetary radius of about 2 AU and solved the spherically symmetric equations of hydrodynamics, along with convective and radiative energy transport. The results showed that, after a brief hydrodynamic adjustment, the planet settled into a quasi-static contraction phase, with radius much larger than that of present Jupiter. After a period of about 10^5 yr, temperatures in the central regions become high enough (2000 K) to dissociate molecular hydrogen. As a result a rapid collapse occurs, ending when the entire planet has come back into hydrostatic equilibrium at a radius of about 4 times Jupiter's present radius, with internal temperatures in the 20,000 to 30,000 K range, and with a luminosity considerably higher than the present value. This calculation was the first to follow the subsequent evolution of a planetary fragment assumed to have formed by gravitational instability.

In my research work on stellar evolution, interstellar hydrodynamics, star formation, and planet formation I have been indebted to many fine collaborators who have provided ideas, insights, detailed discussions, and computer and graphics codes. These interactions have been essential to the successful outcome of many projects. The following list includes those collaborators who have been a co-author with me on at least one published paper or conference proceedings. I believe I have met almost everybody on this list. I also would like to acknowledge the collaborations with Dick Durisen, David Hollenbach, Ralf Klessen, and Hans Zinnecker.

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