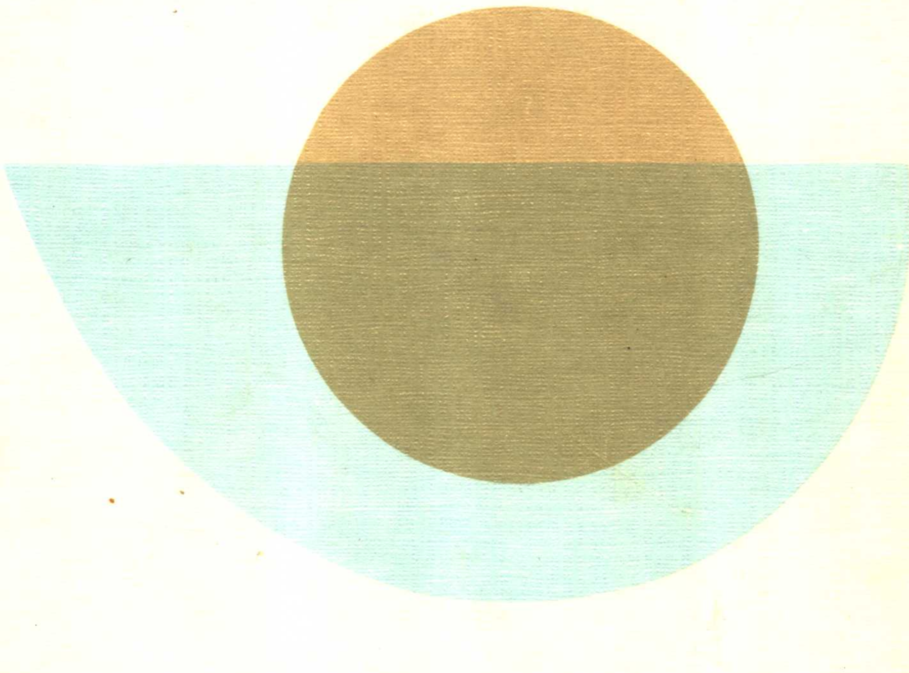
Geophysics and Astrophysics Monographs

Physics of the Sun

Edited by P. A. Sturrock, T. E. Holzer, D. M. Mihalas, and R. K. Ulrich

Volume III: Astrophysics and Solar-Terrestrial Relations



D. Reidel Publishing Company

PHYSICS OF THE SUN

Volume III:
Astrophysics and Solar-Terrestrial Relations

Edited by

PETER A. STURROCK
Center for Space Science and Astrophysics,
Stanford University, Stanford, California, U.S.A.

Associate Editors:

THOMAS E. HOLZER
High Altitude Observatory,
National Center for Atmospheric Research, Boulder, Colorado, U.S.A.

DIMITRI M. MIHALAS
High Altitude Observatory,
National Center for Atmospheric Research, Boulder, Colorado, U.S.A.

ROGER K. ULRICH
Astronomy Department, University of California,
Los Angeles, California, U.S.A.

D. REIDEL PUBLISHING COMPANY

A MEMBER OF THE KLUWER ACADEMIC PUBLISHERS GROUP

DORDRECHT / BOSTON / LANCASTER / TOKYO

Library of Congress Cataloging in Publication Data

CIP data will appear
on separate card

ISBN 90-277-1862-8 (Vol. III)
ISBN 90-277-1823-7 (Set)

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
190 Old Derby Street, Hingham, MA 02043, 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
© 1986 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

PREFACE

This volume, together with its two companion volumes, originated in a study commissioned by the United States National Academy of Sciences on behalf of the National Aeronautics and Space Administration. A committee composed of Tom Holzer, Dimitri Mihalas, Roger Ulrich and myself was asked to prepare a comprehensive review of current knowledge concerning the physics of the sun. We were fortunate in being able to persuade many distinguished scientists to gather their forces for the preparation of 21 separate chapters covering not only solar physics but also relevant areas of astrophysics and solar-terrestrial relations.

It proved necessary to divide the chapters into three separate volumes that cover three different aspects of solar physics. Volumes 1 and 2 are concerned with 'The Solar Interior' and with 'The Solar Atmosphere'. This volume, devoted to 'Astrophysics and Solar-Terrestrial Relations', focuses on problems of solar physics from these two different but complementary perspectives. The emphasis throughout these volumes is on identifying and analyzing the relevant physical processes, but each chapter also contains a great deal of descriptive material.

In preparing our material, the authors and editors benefited greatly from the efforts of a number of scientists who generously agreed to review individual chapters. I wish therefore to take this opportunity to thank the the following individuals for this valuable contribution to our work: S. K. Antiochos, E. H. Avrett, J. N. Bahcall, C. A. Barnes, G. Bicknell, D. Black, M. L. Blake, P. Bodenheimer, F. H. Busse, R. C. Canfield, T. R. Carson, J. I. Castor, J. Christensen-Dalsgaard, E. C. Chupp, A. N. Cox, L. E. Cram, P. R. Demarque, L. Fisk, M. A. Fowler, D. O. Gough, L. W. Hartmann, J. W. Harvey, R. F. Howard, P. Hoyng, H. S. Hudson, G. J. Hurford, C. F. Kennel, R. A. Kopp, A. Krueger, R. M. Kulsrud, R. B. Larson, H. Leinbach, R. E. Lingenfelter, J. L. Linsky, D. B. Melrose, M. J. Mitchell, A. G. Newkirk, F. W. Perkins, R. Roble, R. T. Rood, R. Rosner, B. F. Rozsynai, S. Schneider, E. C. Shoub, B. Sonnerup, H. Spruit, R. F. Stein, M. Stix, J. Tassoul, G. Van Hoven, G. S. Vaiana, A. H. Vaughan, S. P. Worden, R. A. Wolf, and J. B. Zirker.

On behalf of the editors of this monograph, I wish to thank Dr. Richard C. Hart of the National Academy of Sciences, Dr. David Larner of Reidel Publishing Company, and Mrs. Louise Meyers of Stanford University, for the efficient and good-natured support that we received from them at various stages of the preparation of this volume.

Stanford University,
July 1985

P. A. STURROCK

Peter A. Sturrock (ed.) Physics of the Sun, Vol. III, p. xi
© 1986 *by D. Reidel Publishing Company.*

TABLE OF CONTENTS

此为试读，需要完整PDF请访问：www.ertongbook.com

CHAPTER 16

FORMATION OF THE SUN AND ITS PLANETS

WILLIAM M. KAULA

1. Introduction

The Sun formed 4.6 Gy ago, probably as a fragment of a collapsing gas and dust cloud in close association with other stars, from which cluster it was ejected rather early. Conditions in the Galaxy then were not remarkably different from what they are now. Material of the solar system was processed through at least two supernova events within ~200 My before its formation, the last of them recent enough (~2 My) that it plausibly influenced the collapse which formed then Sun.

The planets most likely came from the same cloud as the Sun, since subsequently the interstellar medium would have been much too sparse. Like other collapse phenomena, the Sun's formation was probably accompanied by formation of an accretion disk in which there is a net outward flow of angular momentum and inward flow of mass. This accretion disk, or nebula, is the plausible locus of planetary formation, by some combination of viscous and resonant effects, gravitational instabilities, and accretionary growth. The major problem is the formation of the hydrogen-rich planets, Jupiter and Saturn.

The early Sun was considerably more active, as evidenced by remanent magnetism and implanted inert gases in meteorites; however, isotope anomalies in meteorites also set a moderate upper limit on proton fluxes in the nebula. The relative roles of the solar wind and simple heating in removing gases from the nebula is unsure. Other problems are the high nebula temperatures, >1500 K, indicated by some chondritic meteorites, and hydromagnetic effects.

The Sun alone provides no clues to its formation. Almost the same can be said of the planets, down to bodies at least as small as the Moon. The evidence has been obliterated because all these bodies have evolved appreciably as consequences of energy sources which have been predominantly internal for at least 4.4 Gy. Hence, observations relevant to the origin of the solar system are of (1) small fragments of the system, or (2) comparable properties of parts of the system, or (3) the likely surrounding circumstances, or (4) similar phenomena, or (5) possibly analogous phenomena. Examples in category (1) are the asteroids, comets, and meteorites; in (2), the similarities and differences in composition of the solar atmosphere and meteorites; in (3), the age of the solar system relative to the Galaxy; in (4), the contemporary behavior of T-Tauri stars; and in (5), the spiral structure of galaxies. In some cases the constraints of observations on solar system origin are rather direct and inescapable: e.g. isotopic evidence of the separation

Peter A. Sturrock (ed.), Physics of the Sun, Vol. III, pp. 1–32.
© 1986 *by D. Reidel Publishing Company*

of materials constituting the Earth and meteorites. In other cases the inferences are extremely indirect and entail appreciable assumptions and modeling: e.g. the variety of planetary systems which could be formed in association with a solar-sized star.

The variety of data and theoretical ideas pertinent to the origin of the solar system make the problem a motivator for research in several scientific disciplines, rather than the object of a single coherent discipline. The relevant research can, however, be divided into three general parts: astronomical, cosmochemical, and dynamical.

This review is organized in terms of these three parts, starting with the astronomical because it is most pertinent to formation of the Sun, as distinguished from the solar system. We conclude with a briefer and more conjectural section on the plausible inferences about the Sun and planets which can be drawn from these diverse research efforts.

2. Star Formation

Current astronomical research in the formation of stars is very active, both observationally and theoretically. Most of this research is motivated by considerations other than explaining the solar system, partly because of observational feasibility and partly because of a broader conceptual framework, the drives being more to understand galactic and stellar evolution in general. We report here on those observations and models which bear on solar system formation. We first describe the astronomical context: the structure of the Galaxy, characteristics of stars and the interstellar medium, before concentrating on the observations and models pertaining to star formation.

2.1. GALACTIC STRUCTURE

The solar system is located close to the main plane of the Galaxy about 8 kpc from the center (Oort, 1977). The observable Galaxy is a typical spiral galaxy of $\sim 10^{11}$ $M_\odot$ mass and ~15 kpc radius. About half of this mass is within 3 kpc of the center. The age of the Galaxy is estimated to be ~10 Gy, mainly from the distribution on the H–R diagram of stars in globular clusters. The Galaxy is rotating and appreciably flattened. At the Sun's distance from the center, the period of a single revolution is about 200 My. In the solar vicinity, the half thickness of the Galaxy is about 0.3 kpc. The greatest uncertainty is the amount of mass in burned-out stellar remnants in the galactic halo: perhaps as much as 2×10^{12} $M_\odot$ (Bok, 1981). The Galaxy appears to be evolving very slowly in the Sun's vicinity and probably had a general structure 4.6 Gy ago similar to what it has now.

In the Sun's part of the Galaxy there are irregularities in velocity of ±10% superimposed on the uniform motion around the center (~260 km s^{-1} for the Sun). In addition, there are probably variations in mass density as observed in other spiral galaxies: on the scale of the spiral arms, ~2 kpc wide, perhaps by a factor of 3 or so about the mean for the solar vicinity, ~75 $M_\odot$ pc^{-2}, or 0.125 $M_\odot$ pc^{-3} (neglecting possible invisible remnants in the halo). Of this mean density only ~5 $M_\odot$ pc^{-2} is in the form of interstellar gas. Variations in density of the gas are appreciably greater. Some molecular clouds have $\sim 10^6$ $M_\odot$ within ~50 pc of their centers, an enhancement of more than 200 in density. Some have *OB associations*: groups of massive stars $\lesssim$20 My in age.

The average intensity of the galactic magnetic field is estimated to be $0.2–1.0 \times 10^{-5}$ gauss. Variations of this intensity are correlated with variations in gas density.

此为试读，需要完整PDF请访问：www.ertongbook.com

Dynamical theory suggests that the kinematic irregularities plus gravitational attraction superimposed on general galactic revolution account for the spiral arms (Toomre, 1977; Lin and Lau, 1979). However, the greater local concentrations which are predominantly gaseous probably depend on some sort of hydromagnetic instability.

2.2. Stellar Properties

Main sequence stars range in mass from ~100 to ~0.08 $M_\odot$, and in main sequence lifetime from ~0.01 to ~1500 Gy.

In the vicinity of the Sun, the observed number density of stars, corrected for the death of larger stars, approximates the rule (Scalo, 1978):

$$N \approx 100 \exp[-1.1(\log M + 1.0)^2], \tag{2.1}$$

where N is in $pc^{-2}(\log M)^{-1}$ and M is in $M_\odot$. The ability to fit the power law implies that past stellar formation rates were not significantly greater than the current rate. However, the current nova ($M \lesssim 8\, M_\odot$) and supernova ($M \gtrsim 8\, M_\odot$) rates may be too low to account for the observed abundances of heavy elements in smaller stars, $M \lesssim 1.5\, M_\odot$. Models which reconcile these data generally conclude that in the first few 0.1 Gy of the existence of the Galaxy, when the density of interstellar gas would have been appreciably greater than at present, the rate of star formation would have been greater than now, and a larger portion of the mass would have gone into massive stars. Hence, by the time the solar system formed ~5 Gy later, most of the interstellar matter would have been former stellar material; the gas density, and hence stellar formation rate, would have been only moderately higher than at present; and the major part of the mass would have gone into smaller stars (Bierman and Tinsley, 1974). Hence, circumstances of star formation 4.6 Gy in the past were not very different from what they are now.

The rotation rates of main sequence stars, inferred from Doppler broadenings of their spectral lines, are functions of their mass, with a sharp drop-off in the rotation–mass relationship at ~2 $M_\odot$ corresponding, perhaps, to the change in the energy transfer mode from entirely radiative to convective in the outer layers. The spin-down of smaller main sequence stars is plausibly related to their stellar winds. The present solar wind carries away so little angular momentum that the decay time for solar rotation therefrom is ~10^{10} yr. However, for moderately massive stars, 1.2 $M_\odot$, which are known to be rather young, there are correlations of spin rates and chromospheric emissions presumably dependent (like the wind) on the vigor of convection, indicative of decay times a few times 10^8 yr (Kraft, 1967).

Another important property of stars relevant to their formation is the frequency of their occurrence as members of multiple systems, bound in orbits around each other. Only ~20% of stars are single, like the Sun; ~50% are members of binary pairs, ~20% of triplets, ~5% of quadruple systems, etc. (Batten, 1973). The orbital angular momentum vectors of these multiple systems are random in direction with respect to the angular momentum vector of the whole Galaxy. In a study confined to the 135 stars which are (1) of spectral classes F3 through G2 (masses ~1.5–1.0 $M_\odot$), (2) of declinations $\delta > -20°$, (3) of apparent magnitudes <5.5 (hence within ~30 pc), and (4) primaries in multiple systems, two-thirds were found to have stellar companions. The secondary primary mass ratios divide into two populations according to the period of the binary. For periods greater than 100 yr, the frequency distribution of mass ratios is the same as predicted by a random selection from all stars smaller than the primary. For periods less than 100 yr, the frequency varies with the mass ratio, with a $\sim M^{1/3}$ proportionality. The smallest companion inferred (from the Doppler shifts of the primary's spectrum) was $\sim M_1/16$ in mass, close to the minimum mass star directly observable (Abt and Levy, 1976; Abt, 1978).

2.3. Planetary Indications

Extrapolation of the $M^{1/3}$ frequency to masses below the limit inferable as spectroscopic binaries suggests that all 1.0–1.5 $M_\odot$ stars have companions, the smallest 20% of which are planets, i.e. bodies too small to have the pressures necessary for hydrogen burning. Systematic efforts have been made to detect astronomically unseen companions or stars within ~10 pc: i.e. by periodic shifts of a star against its background. Evidences of shifts have been found associated with stars such as the closest of $\delta > 0°$, Barnard's (a 0.15 $M_\odot$ body 1.8 pc distant), by Van de Kamp (1975). However, the possibilities of systematic errors in this work are considerable (Gatewood, 1976).

2.4. Interstellar Clouds

The density of the interstellar medium (as inferred from absorption of starlight by the dust component or from the 21 cm radiation by the atomic hydrogen component) is about 10^{-24} g cm^{-3}, or 0.6 cm^{-3} for hydrogen atoms. The composition appears to be about the same as the Sun and other stars: by mass, 75% H and 1% dust. The temperature is typically 100 K, but highly variable.

Of more interest for star formation are *interstellar clouds*, concentrations of the interstellar medium by a factor of 100 or more in density, and of 100 $M_\odot$ or greater. Most common are *diffuse clouds*, which typically have radii of 3 pc, densities of 10^{-22} g cm^{-3}, and occur at intervals on the order of 30 pc. Such clouds are still sparse enough to be transparent, and hence are maintained at ~100 K by starlight. When a cloud is more dense, 10^{-21}–10^{-19} g cm^{-3}, it becomes a *dark cloud*, opaque to visible light, and the internal temperature can drop to ~10 K, inferred from radio observations of transitions in carbon monoxide, CO. Greater densities also lead to molecular composition becoming dominant. For sufficiently large combinations of mass ($\gtrsim 10^4\, M_\odot$) and density, several other molecular transitions can be detected, and considerable structure can be mapped by the CO transitions: hence the name *molecular clouds*. In places they may have 10 K temperatures, but elsewhere their temperatures are appreciably elevated by the occurrence of O and B type stars. Two molecular complexes of $\sim 10^5\, M_\odot$ each appear to extend for ~50 pc across the Orion Nebula (Thaddeus, 1977; Evans, 1978).

2.5. Observations of Forming Stars

The only plausible material from which to make the Sun and similar stars is, of course, the interstellar matter. The simplest considerations of a forming star suggest that: (1) it would be close to some concentrated source, such as the clouds described above; (2) its main compositional distinction would be a lithium abundance higher than main sequence stars, like chondritic meteorites; (3) it would have larger radius, because matter is still falling in; (4) it would be more luminous, at least in the later stages, because of the amount of gravitational energy to be radiated away; and (5) it might appear redder, because the visible radiating surfaces (e.g. dust) could still be an appreciable distance from the core, even after the core had achieved sufficient mass to induce H-burning. Hence, there have been searches for such objects associated with clouds appearing above the main sequence in the Hertzsprung–Russell diagram. Particularly valuable to these searches are infrared techniques, because the dust in a dense cloud will absorb visible light and reradiate it at infrared wavelengths (Werner *et al.*, 1977; Strom *et al.*, 1975; Cohen and Kuhi, 1979).

Three categories of objects have been found consistent with the above criteria for young, still-forming stars of approximately solar mass (Strom *et al.*, 1975).

2.5.1. *T-Tauri Variable Stars*

Approximately 630 of these sources have been identified within 1 kpc of the Sun. They are characterized by a variety of spectral phenomena suggesting youth and enhanced activity: more intense lithium lines; Doppler broadenings indicating rapid rotation; Doppler shifts and intensities indicating appreciable mass outflow in most cases (perhaps $\sim 10^{-7}\, M_\odot\, \mathrm{yr}^{-1}$), but inflow in others; various emissions, indicating either a significantly different physical regime than the photosphere of a main sequence star (like the Sun) or a surrounding absorbing medium; and irregular temporal variations, normally by one or two magnitudes (a factor of ~2.5–6 in luminosity L), but in three cases by as much as a six magnitude rise. Some T-Tauri stars are located in OB associations, but others are in the smaller dark clouds. The belief that most T-Tauri stars are 0.2–2.0 $M_\odot$ in size seems to be based partly on the computational models discussed below, and partly on statistics: wherever T-Tauri stars appear, most stars already on the main sequence are more massive, $\gtrsim 3\, M_\odot$, and there is a dearth of less massive stars. The estimated duration of the 10^{-7}–$10^{-8}\, M_\odot\, \mathrm{yr}^{-1}$ mass outflows is also based on a combination of statistics and modeling considerations: perhaps 10^6–10^7 yr (Strom *et al.*, 1975; Strom, 1977; Herbig, 1978).

2.5.2. *Nonemission, Nonvariable Pre-Main Sequence (PMS) Stars*

Almost 50% of the stars occupying the same region of the Hertzsprung–Russell diagram as the T-Tauri stars and associated with clouds do *not* show any exceptional emissions or variability in their spectra. The evidence for a high Li content in these stars is weak. The existence of these stars raises the possibility that the exceptional phenomena observed in T-Tauri spectra are not inherent in forming solar-mass stars, but depend on structural circumstances: most obviously, on being a member of a binary pair (Strom *et al.*, 1975; Strom, 1977).

2.5.3. *Herbig–Haro Objects*

These sources are more diffuse and redder than T-Tauri stars, and are strong in IR emission. Some also have been interpreted as having spectral Doppler shifts indicating mass outflow. They are at locations in cloud and stellar associations where the most recent star formation is expected to be occurring. Hence the evident interpretation is that they are dusty envelopes of matter infalling to a star. An alternative interpretation is that they are the reflections of starlight from surrounding clouds (Strom *et al.*, 1975; Strom, 1977; Herbig, 1978; Schwartz and Dapita, 1980).

2.6. CONDITIONS FOR CLOUD COLLAPSE

We discuss here circumstances relevant to initiation of collapse to a solar-sized star: a fragment of a dark cloud, density ~10^{-19} g cm^{-3}, temperature ~10 K. Significant cloud fragmentation at higher densities has not been observed to occur, and hence the properties at this stage have important effects on star formation processes, and constitute appropriate starting conditions for collapse models (Larson, 1977, 1978, 1981). The simplest model is a spherically symmetric cloud, without magnetic field, rotation, or random motions. The equations of motion then become

$$\rho \frac{\mathrm{d}^2 r}{\mathrm{d}t^2} = -\frac{\mathrm{d}p}{\mathrm{d}r} - \frac{\rho G M}{r^2}, \tag{2.2}$$

where ρ is density, p is pressure, and M is the mass contained within radius r. If the pressure gradient $\mathrm{d}p/\mathrm{d}r$ is zero, as would occur in an isothermal homogeneous cloud with a matching external pressure, then the first term on the right drops out and the equation is solvable for the time required for a cloud with initial radius r_0 to collapse completely:

$$t_f = \frac{\pi}{2}\left[\frac{r_0^3}{2GM}\right]^{1/2} = \left[\frac{3\pi}{32G\bar{\rho}_0}\right]^{1/2}, \tag{2.3}$$

know as the *free-fall time*.

A cloud in dynamic equilibrium will have the left of Equation (2.2) zero. If it is sparse enough to be isothermal ($\mathrm{d}T/\mathrm{d}r = 0$), then, from the perfect gas law

$$p = \rho kT/m = c^2 \rho/\gamma \tag{2.4}$$

(where k is the Boltzmann constant, m is mean molecular mass, c is the sound speed, and γ is the ratio of specific heats), there must be a gradient in density ρ in order to have a pressure gradient $\mathrm{d}p/\mathrm{d}r$ balancing the gravity term. Assume $\rho = Ar^{-n}$ and isothermality ($\gamma = 1$) and substitute in (2.2):

$$0 = c^2 nAr^{-n-1} - 4\pi G \frac{A^2}{3-n} r^{1-2n}, \tag{2.5}$$

whence $n = 2$ and $A = c^2/2\pi G = M(r)/4\pi r$. Thence, for an overall radius R

$$\bar{\rho} = 3c^2/2\pi G R^2, \tag{2.6}$$

and for collapse there is required

$$
\begin{aligned}
M &\geq 2c^2 R/G \\
&\geq 2 \left(\frac{kT}{mG}\right)^{3/2} (\xi\pi\bar{\rho})^{-1/2} \\
&\gtrsim 10^{-11} \left(\frac{T^3}{\bar{\rho}}\right)^{1/2} M_\odot = M_J,
\end{aligned}
\tag{2.7}
$$

for $\bar{\rho}$ in g cm^{-3}. For dark cloud, values of 10 K for T and 10^{-19} g cm^{-3} for $\bar{\rho}$, $M \gtrsim 1\ M_\odot$. M_J is known as the *Jeans mass*.

In a real cloud there are the additional effects of magnetic field, rotation, other internal motions, and external pressure. All these effects, except pressure, act to increase the critical mass for collapse. The assumption of a magnetic field intensity based on freezing the galactic field to the gas and a rotation rate based on the present relative motions between stars would make these effects much more important than temperature in resisting collapse. However, the axial character of these effects emphasizes the unrealism of the spherical model: a magnetic field would not resist collapse along the field lines, and rotation would not resist collapse parallel to its axis. If a dark cloud is as cold as 10 K, then the ionization would plausibly drop sufficiently for the neutral matter to slip with respect to the magnetic field. Shocks would reduce the relative motions to something less than the sound of speed (Mestel, 1977; Mouschovias, 1977, 1978).

The common occurrence of star formation in clusters suggests that external pressure is a significant factor in initiating cloud collapse. Sources of such pressure might be: a strong stellar wind from a newly formed star; or a supernova explosion; or the expansion of an H II region. H II regions have been invoked to explain the progression in age of OB stars along a molecular cloud (Lada *et al.*, 1978).

The considerations of this subsection emphasize that cloud collapse should be highly nonhomologous and asymmetric. These effects will be enhanced by any magnetic field, external pressure, or other inhomogeneity in initial conditions (Mouschovias, 1978; Larson, 1981).

2.7. Models of Star Formation

Although similarity solutions (Shu, 1977; Cheng, 1978) yield significant insight, complications such as opacity and shocks require numerical integration to construct a plausible scenario of cloud collapse to form a star.

So far, only spherically symmetric models without rotation or magnetic fields have been explored in detail for the process complete to stellar densities. It is useful to examine these idealizations as reference models for more complicated computer experiments. For the 10 K, 10^{-19} g cm^{-3}, $1\ M_\odot$ ($R \sim 10^4$ AU) starting conditions, the principal stages of these models are as follows (Bodenheimer and Sweigart, 1968; Larson, 1969, 1977; Winkler and Newman, 1980; Boss, 1980a; Stahler *et al.*, 1980):

Isothermal Collapse. For $\rho < 10^{-13}$ g cm^{-3}, the cloud is transparent. Although heat is generated by the compression consequent on collapse, it is absorbed and efficiently radiated away by the 1% dust component. For any reasonable starting conditions, the model develops a $\rho \propto r^{-2}$ density gradient, as inferred from Equation (2.5).

CORE DEVELOPMENT. When the density exceeds $\sim 10^{-13}$ g cm^{-3}, the central region becomes opaque to infrared radiation, and the temperature rises. The resulting pressures halt the collapse, causing the development of a hydrostatic core. When falling gas hits this core, a shock front develops resulting in the conversion of kinetic energy into heat, and thence into radiation. This energy transfer at the accretion shock is the principal topic on which various numerical integrations differ; a number of devices have been employed (Winkler and Newman, 1980). Within the core, convection should bring about an adiabatic temperature gradient:

$$\frac{dT}{dr} = (1 - 1/\gamma)\frac{T}{p}\frac{dP}{dr}\ , \tag{2.8}$$

where γ is the ratio of specific heats: 7/5 for diatomic molecules and 5/3 for atoms.

HYDROGEN DISSOCIATION. When the temperature reaches ~2000 K, hydrogen dissociates, resulting in a reduction of the specific heat ratio γ and a lowering of the adiabatic gradient, so that further collapse occurs.

FREE-FALL REGION. Just outside the dense core, the motion becomes dominated by free-fall, i.e. at radius r the velocity is

$$v = -(2Gm_0/r)^{1/2}, \tag{2.9}$$

where m_0 is the core mass. This velocity, proportional to $r^{-1/2}$, together with the steady-state continuity equation

$$\frac{\partial}{\partial r}\ (r^2 \rho v) = 0, \tag{2.10}$$

leads to a density $\rho \propto r^{-3/2}$. Consistent with Equation (2.9), the attraction of the central core is dominant in determining the pressure gradient from Equation (2.2) with $d^2r/dt^2 = 0$, $\rho \propto r^{-5/2}$. These two proportionalities in the perfect gas law (Equation (2.4)), lead to $T \propto r^{-1}$. The same proportionality is obtained using the diatomic specific heat ratio, $\gamma = 7/5$, in the adiabatic law, Equation (2.8). These density, pressure, and temperature gradients are sometimes used in models of condensation from the nebula. However, they depend on the aforestated assumptions and neglect of radiative processes affecting the temperature gradient.

LATER DEVELOPMENT. The core continues to maintain a radius of several $R_\odot$ and attains a maximum luminosity of about 30 $L_\odot$ in its growth. The growth time to $L = L_\odot$, $R = 2.0\ R_\odot$, is stretched out to $\sim 4t_f \approx 8 \times 10^5$ yr, most of it close to the main sequence, the later part following the Hayashi (1966) track. See Figure 1.

To infer the effects of rotation, inhomogeneous mass distribution, and magnetic fields,

此为试读，需要完整PDF请访问：www.ertongbook.com