STRUCTURE OF JUPITER AND SATURN

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Abstract. Understanding of the planetary interiors depends upon our knowledge of the equations of state and of the transport properties of matter at high pressures and temperatures. The present status of this knowledge in relation to hydrogen and helium is discussed in detail including electrical and thermal conductivity, viscosity, diffusivity, etc. On this basis the various possible models of the internal structure of Jupiter and of Saturn are presented and their agreement with observational constraints such as the multipole gravitational coefficients analyzed. Relevance of planetary magnetic fields, basic atmospheric information and the Great Red Spot of Jupiter to the models of the interiors are discussed.

1. Introduction

1.1. Scope of present work

Among the giant planets, which lie beyond the asteroid belt, Jupiter and Saturn stand out because of their size as well as because of their many unique and spectacular features such as the Jovian Great Red Spot and the Saturnian rings. They are not only the two most massive and largest planets but also have the lowest densities among all planetary bodies. The very low densities limit drastically the possible choice of chemical composition and facilitate greatly the development of theoretical models of their interiors. The two planets contain 92% of the planetary mass of the solar system and 98% of the total angular momentum of all planets. Their high gravitational fields and the relatively low surface temperatures assure an unusually slow loss of the more volatile elements and thus suggest that both planets are in a certain sense well preserved samples of the chemical composition of the very early solar system. For instance, at present, the mean escape time of hydrogen from these two planets is $10^n$ yr, where $n$ of the order of 100–400 depending upon the assumed model of the atmosphere! It is thus clear that the structure and composition of the interiors of Jupiter and Saturn are of fundamental importance for achieving an understanding of the whole solar system as well as posing interesting theoretical and experimental problems in the physics of light elements at megabar pressures.

As shown in Table I (Section 6.1) certain basic quantities such as mass, radius, oblateness, rates of rotation, lower gravitational coefficients, albedos, brightness temperatures and energy flux are known for both planets though not with the same degree of certainty. From these data it follows that besides being composed mostly of the lightest elements both planets emit much more energy than they receive from
the Sun, that of all planets they have the highest ratios of the equatorial centrifugal to gravitational forces and thus are strongly non-spherical and finally that convection in the interiors as well as in the atmospheres plays an essential role in determining the heat transport and dynamics of the interiors and of the complicated cloud systems.

Satisfactory theoretical models of Jupiter and Saturn should not only account for these observations and conclusions but also they should be compatible with certain unique features of each planet. On Jupiter the striking features are the huge magnetic field, the rotating systems of decametric radiation beams, the Great Red Spot with its unusual aperiodic and periodic motions and the banded cloud structure. On Saturn one striking feature is the apparent absence of a radiation belt which may be due either to an absence of a suitable magnetic field or to the presence of the rings and the other is the almost complete absence of cloud bands.

The main objective of this paper is to present an up-to-date summary of the status of our knowledge of the structure of Jupiter and of Saturn with primary emphasis on the interiors of both planets. Since so much of our understanding as well as of the uncertainty concerning these interiors depends on the knowledge of the equation of state and of transport properties of hydrogen and helium considerable space (Section 2) is devoted to this subject. It becomes apparent that what is necessary is information derived from a 'first principles' theory of the behavior of these elements at high pressures and temperatures and also a semi-empirical approach based on terrestrial analogues and experiments which leads to conclusions about more elusive 'second order' effects. In Section 3 these equations of state and properties are used to arrive at various models of Jupiter which permit understanding of such observations as the heat emission, magnetic field, etc. A variety of models has to be presented since the state of our knowledge does not lead to unique answers. In Section 4 the same is done for Saturn for which the theoretical and observational situation is considerably worse than for Jupiter, and finally Section 5 is devoted to a brief survey of what is known about the structure and composition of the Jovian and Saturnian atmospheres. No details of the exceedingly complicated and often uncertain studies of atmospheric dynamics and properties are given. A discussion of the most recent models of the Great Red Spot is, however, included. The satellites of both planets and the Saturnian rings present many problems of a theoretical and observational nature and must fall beyond the scope of this review. In the remainder of this chapter is given a brief outline of the method of analysis of planetary interiors and the basic observational data.

1.2. Outline of the theoretical methods

Planetary interiors are probably more difficult to study than any other parts or aspects of the solar system because essentially all pertinent information is based on indirect observational evidence and on not too certain theoretical assumptions. The construction of models of planetary interiors consists of obtaining solutions of hydrostatic equilibrium equations using equations of state appropriate to the expected chemical composition of the planet. The latter is deduced from a variety of arguments in-