

### 1.3.2 Atmosphere

Jupiter is much easier to observe from Earth than Saturn, Uranus, and Neptune, and we knew generations before the first Pioneer spacecraft encounter that Jupiter’s atmosphere has fast jet streams, dramatic changes in cloud brightness, and in particular a very old circulation pattern in its southern hemisphere called the Great Red Spot (GRS). Even when the first crystal-clear images from Voyager came back in 1979 showing elegant, Earth-sized turbulence turning in slow motion alongside jet streams that run so true one can predict jovian weather with just a clock and a ruler, there was the sense that the GRS was special, perhaps unique, because there was no obvious analog on Earth or anywhere else. But, by the end of Voyager’s Grand Tour, Neptune’s Great Dark Spot was discovered and the status of the GRS changed overnight from one-of-a-kind to ubiquitous. Today, we even find analogs in Earth’s oceans, called Meddys, which are long-lived anticyclones that persist from one season to the next under the surface of the Atlantic Ocean, and making a GRS in the laboratory or in computer models turns out to be as easy as giving it a try.

Now, the planet itself has reached the status of ubiquity as new extrasolar giant planets are discovered each year, and that means the chemistry and dynamics of Jupiter’s atmosphere take on special significance. We do not have to go outside the solar system to benefit directly from detailed analysis—in Chapters 4 through 9 you will see informative comparisons made between the atmospheres of Jupiter and Earth. Some themes jump out on the topic of similarities. A common theme regarding atmospheres is that they have a minimum temperature somewhere in their middlealtitude region, and they are warmer everywhere else, reaching extremely high temperatures in the thermosphere, and for a giant planet, extremely high temperature in their interior. Thus, if the minimum temperature happens to be too warm for a particular vapor to condense, then clouds of that species will not form anywhere in the atmosphere, no matter how high or how low one looks. This is the case for methane vapor in Jupiter’s atmosphere, and the fact is exploited to give remote-sensing instruments control over what depth they are sampling. Observe Jupiter with a filter that passes only light associated with a methane absorption line and you will see only structure that is above most of the methane and therefore high in the atmosphere; look between the lines and you will probe deeply. Remote-sensing techniques are not described for their own sake in this book, but they are intertwined throughout and especially can be appreciated in practice in Chapters 4 and 5 on the chemical composition of Jupiter’s atmosphere and on the structure of the clouds and haze, and in Chapter 9 on the thermosphere and ionosphere. Interestingly, the remote-sensing techniques and the data from the one in situ probe to date, the Galileo probe, both reach down to about 20 bars. Not surprisingly, a recurring refrain from the authors of all the atmospheres and interior chapters is a wish to send a probe down to 50 or even 100 bars.

A major theme that one finds in this book is Jupiter's helium abundance, because it contains information about the formation of the solar system itself as well as history about the planet. Another is the importance of water. It is understood by school children that the weather on Earth is strongly affected by the action of condensing and evaporating water, but it was not until Galileo that we had definitive proof that the same holds true on Jupiter. On Earth, maritime barometers are labeled "Stormy" on their low-pressure side, and so it may not come as a surprise that the lightning activity on Jupiter occurs predominantly in the cyclonic regions, so named because they turn in the same direction as the sense of the planetary rotation and hence are low-pressure regions (the other way is anticyclonic, implying high pressure), but nevertheless it is somewhat of a surprise, as you will read in Chapter 6. For most of the trace species in Jupiter's atmosphere, except water, the rule of thumb is that their abundance is about three times that seen spectroscopically in the Sun (three times solar), whereas the best one can say for water on Jupiter is that it is a busy substance—extremely heterogeneous—but that is just like on Earth. One gets the sense when reading the atmospheres chapters that Jupiter's meteorology is quite a bit like Earth's in many respects, certainly there is 120 times as much surface area on Jupiter and no surface to stand on (or to collect rain on), but for the most part, Jupiter and Earth are on the same page meteorologically.

One of the major differences that is just now being investigated in numerical weather models for Jupiter is the fact that water vapor is much heavier than jovian dry air (hydrogen and helium), whereas on Earth water vapor is slightly lighter than dry air (nitrogen and oxygen). Consequently, rain should drop like lead shot on Jupiter and after it stops raining, the remaining air is much lighter than before, an effect that is not experienced on Earth. Regarding precipitation, the best terrestrial analog may be rainstorms that occur over deserts in conditions that are so dry that the rain evaporates before it hits the ground. Some of the mystery of Jupiter's dynamic meteorology has lifted like a morning fog. For example, the fact that jovian storms tend to merge on contact is a mathematical consequence of two-dimensional turbulence that has now been well documented in theoretical meteorology and statistical physics. Essentially any source of small eddies will result in large, long-lived vortices, but there remains the fundamental question of how the small eddies are generated—by convection, shear instability, both? Other enduring puzzles include what controls the size and shape of the alternating jets streams and the nature of the abyssal circulation. Most of planetary science relies on passive, remote investigations.

In contrast, modern physics is extremely interested in the workings of atomic nuclei, and one of the most successful means of inquiry into the subatomic realm is the not-too-subtle technique of colliding nuclei together as hard as can be managed. We do not usually have the luxury in planetary science of subjecting our objects of interest to such controlled laboratory investigations, but occasionally Mother Nature herself provides such an experiment. For

Earth, the June 1991 explosion of Mt. Pinatubo, and, not diminishing the subsequent human tragedy, the rich stratospheric data set that resulted comes to mind. In the context of Jupiter, we refer to the events of July, 1994 when the fragments of Comet Shoemaker-Levy 9 collided at precisely known times and positions with Jupiter, the first ever such planetary collision witnessed by humankind. Chapter 8 is devoted to a summary of what happened and what can be learned from it, the effects of the collisions bear on topics in chemistry, impact and explosion physics, magnetospheric perturbations, and long-term atmospheric transport and mixing, not to mention a heightened awareness of Earth's vulnerability, especially to uncharted comets.

The region of Jupiter's atmosphere most accessible to remote-sensing techniques is the stratosphere, and in particular the photochemistry of the stratosphere (sneak a peek at Fig. 7.3 and count the "h" symbols). A central theme that emerges in the discussion of the middle and upper atmosphere is the temperature. In Jupiter's stratosphere, the temperatures and composition are now known to be intimately connected. In the thermosphere, a top question is about the temperature itself, why it is hundreds of degrees hotter than was anticipated based on a theory that is adequate for Earth and Titan, namely, a balance between heating by solar extreme ultraviolet radiation and downward thermal conduction. Chapter 9 explores this question and the chemistry of the upper atmosphere in detail. For those interested in the interaction of Jupiter's powerful magnetic field with its atmosphere, this interplay is central to Chapter 9 and the discussion of stratospheric haze in Chapter 5. The million amps coming into the atmosphere along the circuit that threads through Io literally lights up Jupiter's polar sky. That is to say, if you like your hydrocarbons fricasseed and you like to dance under a strobe of x-rays, then Jupiter's middle and upper atmosphere is the place to be.