Chapter 2
The Ideas of Greeks About Nature

2.1 The Basic Assumptions of Aristotle on Motion and Gravity

Motion was one of the earlier phenomena that were studied by ancient Greek natural philosophers. One might initially assume that motion is a characteristic of life: people and animals move freely, while dead men and stones do not. It is possible of course to make a rock to move, but this usually happens through the impulse given to it by a living being. This initial impression, however, does not seem to withstand a critical approach, since it cannot explain the immobility of plants that are definitely living organisms, while there are also many examples of motion that have nothing to do with life. For example, celestial bodies move in the sky without any apparent cause. The same happens with dust or sea waves, that are raised by the wind. Of course, one could assume that heavenly bodies are pushed by angels, that the wind is the breath of Aeolus, god of wind, and that storms are raised by the trident of Poseidon, god of the sea. Such hypotheses were indeed common in most early civilizations and prevailed until the Renaissance. The Greek natural philosophers, however, tried to propose interpretations arising from the implementation of rational thinking and based on phenomena that are perceptible with our senses. This consideration of nature, therefore, excluded from possible explanations of natural phenomena the angels and the gods of wind and sea.

Another fact that opposes this theocratic interpretation was the existence of cases of motion that could not be interpreted easily as a result of divine influence. For example, the smoke of a fire is not rising vertically, but follows a complex turbulent motion. A stone, that is released from some height above the Earth's surface, moves directly downward, although no one pushes it in that direction. Surely, even the most "fanatical" mystic finds it difficult to accept that every breath of air and every piece of mater contains a small god (or demon!), who pushes them here and there.

The Greek natural philosophers created many philosophical systems, that is, many theories about nature and its phenomena, each based on different hypotheses. These theories were brought together and codified into a single theory by the

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Fig. 2.1 Aristoteles by G. Tsaras; in the campus of the Aristotelian University of Thessaloniki (photo by J. Tsouflides)

Greek philosopher Aristotle (384 BC–322 BC), who was born in Stagira of Chalkidiki (Northern Greece), but studied and taught in Athens (Fig. 2.1). Aristotle's theory was based on the following assumptions:

First hypothesis Earth is the center of the universe.

Second hypothesis All material objects are made of the four elements originally proposed by Empedocles and later adopted by Plato, namely earth, water, air, and fire.

In order to explain the motion of bodies not being pushed by living things, Aristotle put forward an extra third hypothesis:

Third hypothesis Each of these elements has its natural place, or physical location, in the universe.

The natural place of element earth, the main constituent of all solid bodies around us, is the center of the universe. So, all solid matter is accumulated in the center of the universe and creates the world in which we live. The ancient Greeks knew that from all solid geometric shapes with the same volume, sphere is the one that has the smallest surface area. So, if it is correct that every piece of solid matter is accumulated as close to the center of the universe as possible, then Earth must be spherical in shape. In addition, its center shall coincide with the center of the universe.

The physical location of the element water is just above the surface of the earth's sphere, forming a water shell with spherical surface.

The physical location of the element air is just above water.

Finally, the physical location of the element fire is above air.

2.2 Success of the Basic Assumptions of Aristotle

Aristotle's theory was very successful at the beginning, because observations seemed to agree with predictions. As far as we can, at least, understand with our senses, Earth is spherical and is located in the center of the universe, since we are surrounded by a hemispherical dome (the sky), where the celestial bodies (stars and planets) are moving. Oceans cover large areas of Earth's surface (we now know that they cover about 2/3 of it), so water is indeed over earth. Air surrounds earth and sea. Finally, during storms, high in the atmosphere, occasionally appear indications of fireballs in the form of lightning. The same theory can even explain the behavior of objects that do not consist of "pure" elements. For example, wood floats in the water because it is a mixture of earth and fire. When wood is burned, the fire is released and moves upwards, while the remaining "earth", the ash, cannot float on the water anymore and heads towards its natural place, below water.

Furthermore, the hypothesis of "natural place" could explain the phenomenon of motion. Assuming that there is a natural place for everything, it was very reasonable to deduce that whenever an object is removed from its normal position, it tends to return to it at the earliest opportunity. For example, a stone, held by someone in the air, manifests its "tendency" to return to its natural place by "pushing" the hand downwards. We could conclude that this is why the stone has weight. This explains why, if we release it, the stone will fall immediately to the ground, that is, towards its natural place, without having to assume the intervention of any "higher power". By similar reasoning, we can explain why tongues of fire move upwards, why pebbles sink when they are thrown into the water and why air bubbles rise in a glass of beer.

A similar reasoning can also explain the phenomenon of rain. When the sun's heat evaporates water (converts it to air according to Aristotle), water vapors rise spontaneously, seeking their natural place, which is over earth and water. But once vapor is condensed, the resulting water falls in the form of drops towards its natural place, which is the region below air but over earth.

Using the hypothesis of "natural place", one may arrive to more advanced conclusions. Suppose we know that an object is heavier than another. The heavier object shows greater tendency to return to its natural place. Indeed, observations seem to confirm this conclusion, since light objects such as feathers, leaves and snowflakes fall slowly, while stones and bricks fall faster. By symbolizing the weight of a falling body with B and its velocity with v, we can express Aristotle's hypothesis of natural place, using modern mathematical notation, with the following equation:

$$\mathrm{v} = ds/dt = k \cdot B$$

where k is a constant. Of course, today we know that the mathematical relation which describes correctly the phenomenon is Newton's second law (axiom):

$$g = d^2s/dt^2 = [1/m] \cdot B$$

where g is the gravitational acceleration and m the mass of the body. It should be noted that Aristotle never made explicit reference to a relation of the form $v = k \cdot B$, because, unlike Plato, he believed that natural laws are not described quantitatively by mathematical relations, but only qualitatively. Aristotle's later disciples, however, believed indeed that an object weighing $2B$ falls twice as fast as another object weighing $1B$.

2.3 Failure of the Underlying Assumptions and Need to Adopt New Ones

Apart from the *spontaneous* or *natural motion*, which involves objects moving to their natural place, Aristotle identified also *forced motion*, in which objects are moving away from their natural place, sometimes seemingly in the absence of an external force. Consider, for example, a stone which is thrown vertically upwards. Initially, the motion of the stone is due to the force applied by the muscles of our hand; however, after our hand ceases to be in contact with the stone, it cannot have any effect to it. So, why the stone does not start falling as soon as it leaves our hand, but continues to move upwards for some time? To explain forced motion, Aristotle formulated an additional fourth hypothesis, this of *antiperistasis* or of the *existence of an intermediate medium*:

Fourth hypothesis According to the hypothesis of antiperistasis[1] introduced by Plato, air "displaced" from the front of the stone moves to its back and "pushes" it forward. But as the "push" is transmitted from one point of the air to another, it slowly weakens and allows the natural motion of the stone to prevail. As a result, the upward motion slows down and eventually reverts to a downward motion, causing the stone to hit the ground. Aristotle modified slightly Plato's hypothesis of antiperistasis, stating that our moving hand sets to motion successive layers of air, which, in turn, push the stone. As the "force" is transmitted from one layer of air to another, it decays and finally the natural downward motion of the stone prevails. In what follows, we will refer to both variants of this hypothesis as "antiperistasis".

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[1] *Antiperistasis* (in Greek means *mutual substitution*) was not a new hypothesis, since it was conceived initially by Empedocles.

With the available, at that time, observations, which did not include initial velocities large enough for a body to escape Earth's gravitational attraction, one may conclude that no force of any nature exists—neither our hand's nor even that of a catapult—that can eventually overcome the natural motion of the stone. Therefore we may conclude that natural motion always prevails over forced motion, and bodies always end up at rest in their natural position. The final conclusion of the Aristotelian theory, then, is that the natural condition of bodies, when no force is acting on them, is the state of rest, that is, the absence of any motion.[2]

The above interpretation of motion cannot, however, include the motion of celestial bodies. For example, while the natural motion of various bodies on Earth is straight (rectilinear), either upward (smoke, fire) or downward (stones, rain), heavenly bodies seem to follow a circular motion around Earth. Aristotle concluded that there was a need for a fifth hypothesis:

Fifth hypothesis The sky and the heavenly bodies are made of a substance that is neither earth nor water, air or fire. It is a fifth element which, following the ideas of earlier natural philosophers (Philolaos, Xenophanes and Parmenides), he named *aether*.[3] The physical place of this fifth element was beyond the realm of fire, outside the Moon's orbit.

The explanation of the motion of celestial bodies stems from the fifth hypothesis, in conjunction with a sixth hypothesis:

Sixth hypothesis The laws governing the motion of celestial bodies are different from those governing motion on Earth. So Aristotle arrived to the conclusion that, while in the region of universe inside the Moon's orbit the natural state of objects is rest, in heaven the natural state of objects is eternal circular motion.

The practical application of Aristotle's hypothesis for the motion of celestial bodies, namely the geocentric theory of the Solar System, was formulated mathematically by the Greek astronomer Hipparchus (ca. 190 BC–ca. 120 BC). Later, it was perfected by the Greek astronomer Claudius Ptolemy (ca. 85 AD–ca. 165 AD) and published in his book *Almagest* (Greater Astronomical Treatise), which was used as the basic astronomy textbook for fifteen centuries (Fig. 2.2). The geocentric theory of Ptolemy, as a consequence of Aristotle's theory of motion of celestial bodies, was, of course, wrong. Both theories were debunked by Galileo, with the performance of the first historically recorded experiments (free fall of bodies and observational confirmation of Aristarchus' heliocentric model). As we shall see, later Newton showed that both the "natural" downward rectilinear motion of bodies and the eternal circular motion of the planets are caused by the same force, the force of gravity.

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[2] We note that this is essentially a special case of Newton's first postulate (axiom), whereby, if no force acts on a body, then it either moves with constant velocity or stays at rest.

[3] A word used by Homer and Hesiod to describe the *fresh air* above the atmosphere or the clear light of heaven (the Greek verb *αἴϑω* means *to burn*).

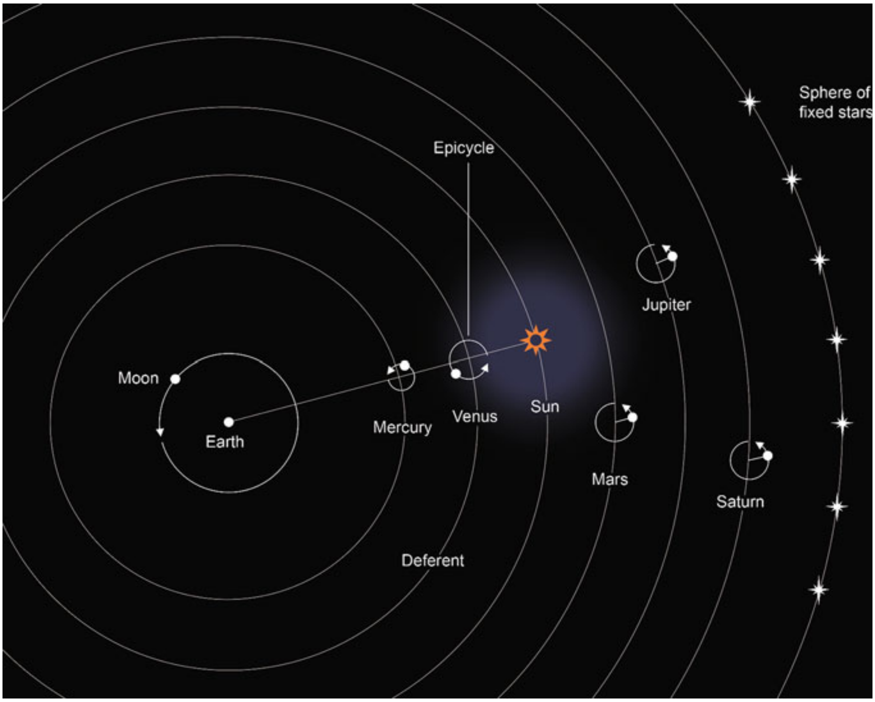

Fig. 2.2 Ptolemaic model of the solar system. In this model the visible with naked eye (from Earth) bodies of the solar system are moving on circles (epicycles), whose centers move in circular orbits (deferents) around the Earth (not in scale, drawing by author)

Finally, we should mention an interesting analogy. Aristotle's contribution in physics was mainly in mechanics and gravity, but in a special way, since according to him, the cause of motion was just gravity. Galileo and Newton, the first two great physicists of the modern era, also made significant contributions to the above mentioned branches of physics, with one difference: they showed that between these two phenomena, motion and gravity, there is not necessarily a cause-effect relationship.

2.4 Critical Review of Aristotle's Theory

Today we know well that Aristotle's theory of motion, as well as Ptolemy's geocentric theory, were completely wrong; both theories have been replaced by Galileo's and Newton's theory of motion and Aristarchus' heliocentric model. But we also know that the theories of Aristotle and Ptolemy were taught for at least fifteen centuries, without being seriously challenged. Instead, Aristotle had come to be considered an "authority" in scientific matters. Was it really impossible for scientists during this long period to test the "correctness" of these two theories? Let's see in more detail how this could have been done.

2.4.1 Internal Contradictions

A logical method to challenge a theory is to show that it can lead to two completely opposite conclusions, which means that it contains internal contradictions and therefore is not self-consistent. For example, the assumption that the Sun is made of aether leads to a contradiction. According to Aristotle, hot or cold objects are made from one of the four elements of the sublunar world and, for this reason, they are "imperfect"; as a result, hot or cold objects exchange heat with their environment over time and eventually end up in thermal equilibrium with it. But heavenly bodies beyond the Moon are made of the fifth element, aether, and therefore are "perfect" in the sense that they do not change with time and follow an eternal circular motion. According to this reasoning, the Sun, which the ancient Greeks knew that lies farther away than the Moon, cannot be hot, which gives rise to the question how is it possible to radiate light and heat (in modern terminology: infrared radiation).

If we restrict ourselves to Aristotle's theory of motion, an argument that leads to a contradiction is the following: A stone falls more slowly in water than in air; according to his theory, the speed of the falling object is inversely proportional to the density, ρ, of the ambient medium, i.e., in modern mathematical notation:

$$v \sim 1/\rho$$

So, the less dense is the medium through which the stone falls, the faster it moves. In a medium with half the density of air the stone would fall twice as fast as in air, while in a medium with one tenth the density of air the stone would fall ten times faster. In the absence of a medium (if the stone falls through vacuum), the stone would fall with infinite speed! On the other hand, the Aristotelian theory also states that a stone, after it is thrown, maintains its initial direction of motion because of antiperistasis—namely, the "force" that air is exerting to the stone. If air is removed, there would be nothing to move the stone through vacuum! Which of the following two conclusions is therefore correct? The stone will move with infinite speed through vacuum or the stone will not move at all? Each conclusion seems equally reasonable! This contradiction has been known since Antiquity, but it was bypassed by the introduction of an additional seventh hypothesis:

Seventh hypothesis There can be no vacuum in nature (hence the famous saying of the great philosopher Spinoza, "Nature abhors a vacuum").

We should note that it is possible to find other ways to solve the above logical dilemma, such as to assume that, in vacuum, bodies moving towards their natural place have indeed infinite speed, but in that case forced motion is not feasible.

Another reasoning, in the context of Aristotle's theory of motion, leading to a contradiction is the following: Suppose we have two stones, stone A weighing one

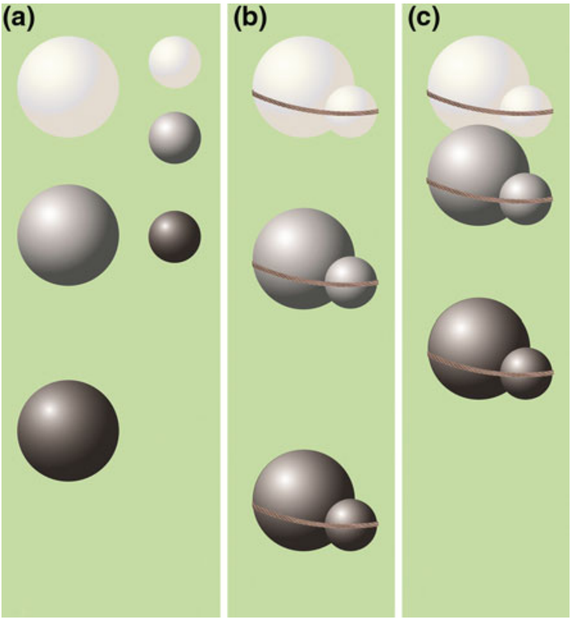

Fig. 2.3 The motion of falling bodies according to Aristotle's ideas. The positions of a heavy and a light stone are depicted at three consecutive time instants (*white*, *light gray* and *dark gray*). Aristotle's theory predicts that the heavier body will fall faster (**a**). But if we tie the stones together we arrive at a contradiction, because the theory predicts that the bound stones might fall either faster (**b**) or slower (**c**) (see text, drawing by the author)

newton[4] and stone B weighing two newtons. According to Aristotle's theory, stone B is heavier and has a greater tendency to move towards its natural place (Fig. 2.3). Therefore, if we let them fall simultaneously, stone B will fall faster than stone A (Fig. 2.3a). Assume now that we bind the two stones tightly with a piece of string and let them fall again. What will happen then, according to Aristotle's theory? Stone B will tend to fall faster than A, but it will be "hindered" by stone A, which will tend to fall slower. In contrast, stone A will tend to fall faster, as it will be carried away by stone B. Therefore, the falling speed of the system consisting of the two stones will be higher than the falling speed of stone A alone, but lower than the falling speed of stone B alone (Fig. 2.3c). This *gedanken experiment*, however, can also be examined from another perspective. Since stones A and B are in contact, they form a stone C weighing three newtons, which, according to the theory, should fall with higher speed than stone B alone (Fig. 2.3b)! Which of the two eventually happens? The system consisting of stones A and B tied together will fall faster or slower than stone B? According to Aristotle's theory, both answers seem correct. Again, one could find a logical way to solve the dilemma; for example, one might assume that the falling speed of the two bodies in contact depends on how tightly they are tied together.

Reasonings like the previously described, which result in logical contradictions, can identify the weaknesses of a theory, but can rarely offer convincing arguments

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[4] Newton is the unit of force in the SI system and it is equal approximately to the weight of a 100 g mass.

against it. The reason is that, as the great epistemologist Thomas Kuhn (1922–1996) said (and becomes apparent from what we have said on the successive "corrections" of the initial hypotheses of Aristotle's theory), "When anomalies occur, they (the scientists) usually devise numerous articulations and ad hoc modifications of their theory in order to eliminate any apparent conflict".

2.4.2 Experimental Verification

Another method to test a theory, which in fact has become even more useful in practice than the one mentioned in the previous paragraph, is to arrive at a logically necessary consequence of the theory and then verify experimentally the result. Let's see how we can apply this method to Aristotle's theory of motion. Suppose we have again two stones A and B, which weigh one and two newtons respectively. According to the mathematical relationship

$$v = ds/dt = k \cdot B$$

mentioned in Sect. 2.2, stone B will fall twice as fast as stone A. One way to "test" this prediction of Aristotle's theory of motion would be to conduct an experiment. That is, to measure the speed at which the two stones fall and to find out if stone B actually falls twice as fast as stone A. If it does, then we could continue to use Aristotle's theory to interpret the motion of bodies. If not, then surely Aristotle's theory should be modified.

But although it was difficult in Antiquity to conduct experiments that require measurements, it is remarkable that the ancient natural philosophers did not consider making simple, *comparative* experiments. For example:

- According to Aristotle, an arrow continues to move after leaving the chord of an arc, due to the "push" it receives from the air through the phenomenon of antiperistasis. Is it possible to put an arrow in motion only by blowing air to it, yes or no?
- A tree leaf falls slowly. The same leaf crumpled falls with the same speed, yes or no?

Unfortunately, such an experimental control was not performed either by Aristotle[5] or by any other natural philosopher during the 2000 years that followed,

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[5] It is worth noting that the first to point out the importance of experiments in natural philosophy was Aristotle himself, in his book "On the generation of animals" (Book 3, Chap. 10), where he writes: "Such appears to be the truth about the generation of bees, judging from theory and from what are believed to be the facts about them; the facts, however, have not yet been sufficiently grasped; if ever they are, then credit must be given rather to observation than to theories, and to theories only if what they affirm agrees with the observed facts." (Translated by Arthur Platt, The University of Adelaide). Unfortunately, later scholars commenting on Aristotle's works did not pay the proper attention to this point. Thus, they came to believe that the works of Aristotle include all knowledge about the world and therefore experiments are unnecessary!

with the exception perhaps of John Philoponus, to whom we will refer in the next section. There are three possible explanations for this failure:

The first is theoretical. Ancient Greeks developed, in a highly successful manner, geometry, which deals with abstract concepts such as dimensionless points and lines without thickness. In this way, their results achieved great simplicity and generality, which could not have been otherwise reached by measuring real objects. Thus, they developed the notion that the real world is not suitable, as a model, to attempt to create abstract theories of the universe. Of course, there were Greek scientists of the Hellenistic era who designed and conducted experiments, as we shall see in the next chapter. The prevailing view, however, both in ancient Greece and the Middle Ages, clearly supported the deduction of conclusions from hypotheses, rather than the testing of theories through experimentation.

The second explanation has to do with the prevailing notion in ancient Greece that manual work was not appropriate for free citizens and that it should be carried out only by slaves. Since experiments required manual labor (beyond scientific knowledge), they were not considered as an acceptable activity for natural philosophers.

The third explanation was practical. In ancient times it was not easy to conduct experiments based on measurements. Today, it seems easy to measure the speed of a falling body, because we have accurate clocks and precise electronic methods of measuring small time intervals. Suffice to say that accurate instruments capable of measuring short time intervals became available only three centuries ago, let alone the fact that, before that, instruments of any kind were extremely rare and expensive.

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