

THE UNIVERSE AT LARGE

Astrophysics Faces the Millennium II **The Stained and Spotty Heavens**

by VIRGINIA TRIMBLE

*Fabricius finds certain
spots and clouds in
the sun.*

—Robert Burton (1577–1640)
Anatomy of Melancholy, Part II, Sect. 2.

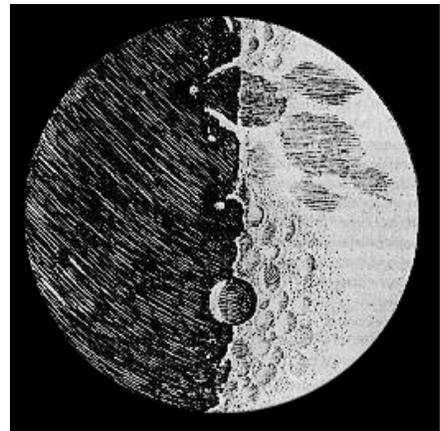
“Immaculate” is, most literally, “unstained,” with a variety of extended meanings in the directions of perfection, exact circular or spherical shape, freedom from sin, and really unlike my kitchen floor. Though terrestrial objects could be any old shape or mix of colors, heavenly ones were supposed to be immaculate in the medieval synthesis associated with the name of Thomas Aquinas (1225–74). The idea sounds a bit less strange if you keep in mind that farther from Earth meant nearer to G.d, who was, by definition, perfect.

The concept was necessarily from the beginning a bit fuzzy at the edges. The only way to miss seeing light and dark areas on the moon is to avoid ever looking at it except in its thinnest crescent phase—early to bed, early to rise, and all that, though myopia at the -9 diopter level or more also works. Well, OK. The moon was just at the edge of the terrestrial/celestial divide, accounting for its stains. But the presence of mountains, capable of casting shadows, was an unwelcome surprise to many who heard or read Galileo’s 1610 announcement. Incidentally, his drawings were actually pretty good, and the shadow patterns in the earliest versions can be associated with particular lunar features, though later reproductions tended to degrade to something like “chicken pox of the limb.” Sporadic handles or appendages on Saturn were similarly worrisome that same year, and not until the winter of 1655–56 did Christian Huygens recognize the phenomena as being due to a thin, tilted ring, which we see in

different orientations through the planet's 30-year orbit period. Apparently those long Dutch winters can be used in many ways.

But it seems to have been dark spots on the supposedly immaculate Sun that caused the most distress. Wait a minute, you will be saying. Surely there are naked-eye sunspots. There are indeed, at least on hazy, dusty, or foggy days, when the Sun is fairly close to the horizon. Chinese and Korean astronomers had recorded something like 150 examples between 165 BC and about 1400 AD (when perhaps Western ideas of what you were supposed to see on the Sun began reaching them). No Far Eastern drawings of sunspots from this period have been found so far, but spots are described as like swallows, magpies, and various other birds. Since they were known to last for days, one cannot suppose there was any confusion with silhouettes of actual birds, but only a search for descriptions that could be interpreted as favorable to the astronomer's current or prospective boss.

Arab and European astronomers very occasionally noted sunspots between 800 and 1400. Climatic conditions, lack of interest, and sunspot cycles of various lengths can be invoked to explain the rarity of Western reports. (It has also been widely claimed that Europe was very cloudy the year the supernova of 1054 was visible from China.) But only a definite mind-set on the part of the reporters can account for all the Arab and many of the European sightings being attributed to transits of Mercury and Venus. Transits of Mercury are never naked-eye events, for its disk is only 12 arcseconds across. Those of Venus are exceedingly rare, and modern computations show that none of the spot reports came from days of real transits. In addition (and this would have been



A reproduction of a reproduction of a reproduction of one of Galileo's early drawings of the moon. It shows the sunrise limb, with shading that makes clear that the circular features have raised, mountain-like edges and lower centers. Galileo also described the lunar maria ("seas"), thinking they were filled with water, as did many later generations of astronomers.



Sunspot drawing in the *Chronicles of John of Worcester*, from 8 December AD 1128. Notice the depiction of the penumbra around each spot. (Courtesy Corpus Christi College, Oxford, Ms 157, p. 380)

obvious to any rocket scientist of the year 831 who thought about the issue), such transits can last only a few hours, while sunspots sometimes remained visible for a week or more. The observers simply did not want to see, or admit to having seen, spots on the Sun. The one pre-telescopic drawing, from England in 1128, carries a caption that, in recent translation, speaks of “two black spheres against the Sun,” that is, once again, intervening bodies of some sort.

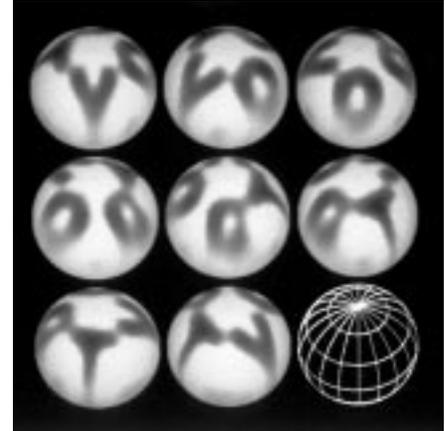
Galileo proclaimed that the spots were intrinsic to the Sun, changing apparent positions because of solar rotation. And that I mention him first is an example of the common injustice called the Matthew effect. Thomas Harriot in England had turned telescope upon the spots earlier than Galileo, and Johann Fabricius of Frisia (look it up; you have a *Gazateer!*) had proclaimed them to be surface phenomena, tracing the solar rotation, first as well. Indeed the contrary, “satellites of the Sun,” hypothesis was also already in print, from Scheiner, a German Jesuit, before Galileo’s *Letters on Sunspots* reached paper. None the less, when *Physics World* asked its readers to vote for the most important physicists of the last thousand years, Galileo got a lot more votes than Harriot and Fabricius. Admittedly, he was first past the post on a great many other issues.

Perfect circles had already suffered one blow that decade, when Kepler’s *New Astronomy* (1609) declared that the orbits of the planets must be ellipses (with the Sun at one focus; $P^2 = a^3$; and the equal areas law) in order to match planetary positions in the sky at the accuracy recorded by Tycho Brahe. Kepler nevertheless attempted to preserve one part of the heavens for geometry, by deriving the spacings of the planets (that is the a values) from a nesting of the platonic solids. The algebraic version is the 18th century Bode’s law, not, of course, a law or first thought of by Bode or Titius. And the 1999.99 explanation of the spacing of the planetary orbits involves both tidal interactions and some chaos, in which Jupiter, Saturn, Uranus, and Neptune may all have formed about the same distance from the Sun and kicked each other around and out. The computations are close relatives of those being used to account for “hot Jupiters,” massive planets orbiting other stars in short-period orbits.

OTHER SPOTS

Well, that is what became of Kepler’s platonic solids. What about various kinds of spottiness and acircularity over the years? The Great Red Spot on Jupiter was discovered in 1644, and had not necessarily been there forever, waiting patiently. Its size, color, and location all vary, and smaller spots on both Jupiter and the other Jovian planets definitely come and go. A completely fictitious tale records what might have happened in 1688 or thereabouts, if Newton had tried to describe his universal gravitation before a modern-style meeting of the Royal Astronomical Society (not founded until the 1820s). The end point is an elderly fellow garumphing, “Well, young man, and can this wonderful new theory of yours explain the Great Red Spot on Jupiter, one of the most puzzling phenomena of the solar system?” The answer, of course, is no. And we can claim at least enough understanding today to recognize that A. Fellow was asking a silly question. The Red Spot was a Taylor column when I was a girl. It is now, very crudely, part of the Jovian weather pattern, and so rather different from sunspots, which are regions of concentrated solar magnetic field.

A computer-generated rotating, spotted star and its reconstruction from simulated spectroscopic data (shapes of absorption lines produced in the cooler gas of the dark regions). The coordinate grid at lower right shows the location of the rotation pole. The time sequence of snap-shots in both the original "star" and its reconstruction runs left to right across top, middle, and bottom of each drawing as the star rotates clockwise as seen from above. (Courtesy Steven S. Vogt, UCO/Lick Observatory)



Once both the spottiness and the starriness of the Sun were part of the astronomical armamentarium, star spots were a natural extrapolation. The 17th century French priest-astronomer, Ismael Boulliau, proposed that variable stars, of which some dozens were by then known, were spotted like the Sun, but much more extensively, so that their apparent brightnesses could vary by factors up to ten or more through their rotation periods. Boulliau is sometimes held up as a Horrible Example of the perils of unjustifiable extrapolation. And indeed most variable stars are pulsating singletons, eclipsing pairs, or unsteady accretors of gas from their surroundings.

But other stars are spotted, they do rotate, and a careful watcher can see the periodic brightness variations, though they are generally at most a percent or so of the total brightness. The record (185 percent) is held by a very young and otherwise fairly peculiar star. In fact you can do better than just see the amount and period of the brightness variations. By concentrating on the shapes of the absorption lines that are strongest in cool gas, you can locate particular spots in latitude on the star, watch them move across in longitude through the rotation period, and follow fading old and growing new spot complexes. The idea, now called Doppler tomography, goes back to a 1958 symposium presentation by Armin Deutsch of Mt. Wilson Observatory.

Much of the recent implementation has been the work of Steven Vogt of Lick Observatory, who, in a triumphant vindication of the method, was able to recover an artificial spot distribution put on a virtual star and turned into Doppler line data by a challenger. The spot pattern spelled out VOGT across the star. You can see why this was not done by an astronomer named Fritze-von Alvensleben. Actually there is another reason. She works on extra-galactic topics.

Analysis of star spots in this way provides much of our knowledge of stellar rotation rates and levels of activity as a function of star mass, surface temperature, and age. The data are complimentary to those coming from X-ray and radio observations and from monitoring emission lines of stellar chromospheres and coroneae. Direct Zeeman measurements of magnetic field strengths in ordinary star spots is only just becoming possible. Many are in the 100s–1000s of Gauss range characteristic of the Sun. And, if you want to be really spotty, it is important to be young, rapidly rotating, and possessed of a deep convection zone. Eating chocolate probably doesn't matter.

The spottiest, fastest-rotating, most active stars tend to have polar spots rather than equatorial or mid-latitude solar-style ones. Activity cycles, like the 11-year solar one, are fairly common. Periods range from 5 to at least 20 years (perhaps an observational limit). The most-active stars with the most spots vary in coverage and emission line strength, but are not obviously cyclic.

POLAR SPOTS

Have we exhausted the possibilities of star spots in modern astronomy? By no means. White dwarfs and, especially, neutron stars with strong magnetic fields have extremely uneven surface emissivity,* generally brightest at the magnetic poles. The magnetic poles are oblique to the rotation ones, and gas can stream in or out along the field lines. One category of stars with polar magnetic spots you have been hearing about for 30+ years. They are the pulsars. Some classes of binary, variable X-ray sources also feature spotty neutron stars. The spots can be hot or cool as well as high or low in magnetic flux. Similar, though less spectacular, variability characterizes magnetic white dwarfs accreting from fluffier companions. The classes are called DQ Her stars, intermediate polars, and other names of at most moderate informativeness.

Let us pay one last visit to the solar system to look at some bodies that can be both spotty and non-spherical. I mean the smaller moons, asteroids, and comet nuclei. They too vary in brightness as they rotate, and we can separate the effects of shape and of reflectivity only for those whose images are resolved. Saturn's moon Hyperion, on the one hand, comes close to being black on one side and white on the other, while Mars' Phobos and Demos are shaped like primitive stone tools whose flint-knapper gave up in the middle of the task. Physically possible rotation periods range from a few minutes to many years. Most are of order a day.

SPHEROIDS, ELLIPSOIDS, AND HIGHER-ORDER ASYMMETRIES

Most astronomical objects large enough for gravity to beat electromagnetism are, in fact, rather spherical. This includes moons, planets, stars, large star clusters, galaxies

**Apologies for the pompous phrase. It is near the end of the semester, and I feel a sudden desire to take advantage of speaking to adults with considerable knowledge of science beyond what I have been able to tuck into students' reluctant crawls over the past 14 weeks.*

(at least the dominant gravitating mass), and the larger clusters of galaxies. The most pervasive and conspicuous deviations arise from rotation, and it is customary to begin by invoking the names of Maclaurin and Jacobi and equilibrium figures of rotation for spheroids and triaxial ellipsoids. (Yes, you may have a moment off to go look up which is which and to get a cup of coffee while you're at it). Modern calculations include effects of pressure, general relativity, and whatever else may be necessary. The usual starting point is a book by Chandrasekhar, and, occasionally, one by R. A. Lyttleton. Herewith a few interesting cases.

For stars, the amount of rotational distortion can be thought of as probing either their density as a function of radius or whether the internal angular velocity is the same as that of the surface. "No major surprises," is a reasonable summary. But readers in late youth may recall that Robert Dicke, in the 1960s, suggested our Sun might have a rapidly rotating interior. This would produce a large second (quadrupole) moment of inertia, J_2 , which, in turn, would be responsible for some of the measured advance of the perihelion of Mercury, leaving less to be accounted for by non-Newtonian gravity. Dicke also had a theory of gravity, with both scalar and tensor potentials, that just nicely produced somewhat less perihelion advance than you expect from general relativity. His goal was to make gravity in some sense "more Machian," so that local processes reflect the properties of the whole universe. I have no opinion on whether Brans-Dicke or any other scalar-tensor theory succeeds with this mission. It is perhaps worth noting that non-GR theories come along every few years, and recent proponents of them have simply sat back and waited for someone else to do the work of testing them.

Dicke, however, set out to measure the shape of the surface of the Sun as precisely as possible. And, indeed, he found the equatorial diameter to be larger than the polar diameter by just about the amount (parts in 10^5) needed to make all the beans come out even. He was, it now seems clear, doing solar surface physics by a very difficult method. The initial observations were made near the peak of a solar cycle, when facular areas near



Robert H. Dicke, inventor of the Dicke (switching) radiometer, the Brans-Dicke theory of gravity, and much else. In 1965 he and his group were in the process of instrumenting a radio antenna to look for radiation left from the Big Bang when Arno Penzias and Robert W. Wilson found it while studying the microwave sky for communication purposes. He received the Tinsley Prize of the American Astronomical Society shortly before his death and deserved many more. (Courtesy AIP Emilio Segrè Visual Archives)

the equator make those regions brighter than high latitudes, and Dicke's method was sensitive to extra brightness, as well as extra area, near the equator.

The modern calculated value for J_2 is 1.6×10^{-7} , and the observational upper limit, from lunar libration, is 3×10^{-6} , about an order of magnitude smaller than what Dicke had in mind. Analysis of solar normal modes (helioseismology) now says independently that the interior is not rotating significantly faster than the surface.

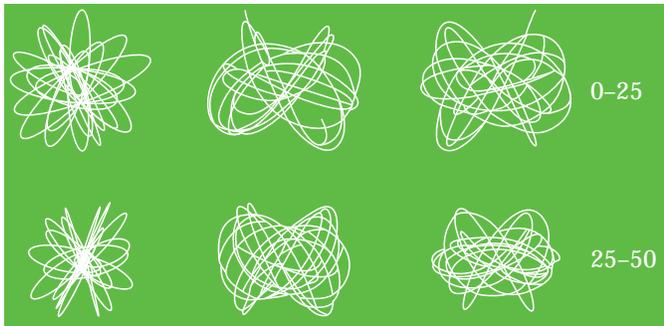
Galaxies, in contrast, have provided some surprises. You already know that the bright part of a spiral galaxy like ours is a rotating disk, usually somewhat flatter than a pancake, but not quite as flat as a tortilla. Less obvious is that spirals also have old stars and globular star clusters whose distribution is much more nearly spherical, and which do not share the rotation of the disk. But you probably know, too, that most of the mass in these

galaxies is not in either the disk or the visible halo. It is the notorious dark matter, and determining the shape, let alone the rotation speed, of something you cannot see is a bit of a challenge. Indirect information comes from the orbits of the halo stars and clusters and from the flaring of the thin disk far from galactic centers. The best fit shape is an oblate spheroid. Axial ratios from 0.9 down to as small as 0.3 have been claimed. The short axis is (obviously?) perpendicular to the disk. Dark halos may even be somewhat triaxial.

Elliptical galaxies were long assumed to approximate maclaurin spheroids. They certainly look it, at first examination. A confirmatory measurement of the rotation speeds of the more squashed-looking ones was not, however, easy to come by. Spirals have emission lines from both ionized and neutral gas in their disks, relatively easy to record on a photographic plate or with a radio telescope. Ellipticals do not. All you have to go on is the sum of the absorption lines from the spectra of their constituent stars. I actually asked to be allowed to try to measure elliptical rotation curves as my Ph.D. dissertation and was told no. And a good thing it was; I would have found no rotation, and nobody would have believed that this was the right answer.

The first persuasive data came a decade after (1977) from Garth Illingworth (his dissertation, it turns out). Ellipticals, even highly flattened ones, generally don't rotate, he found. And so it remains. Modeling what they actually do has become an important topic in galactic dynamics, and the last subject to which Martin Schwarzschild made a major contribution. On the observational side, the deconvolution of many two-dimensional distributions of brightness on the sky into possible three-dimensional distributions of luminosity in space has gradually led to the official word being "triaxial."

The problem for theorists is then to figure out a gravitational potential shape within which visible stars can move to produce the observed luminosity distribution and the line widths (velocity distributions) along various sight lines through the galaxy that we measure. Schwarzschild's contribution was to insist that, when you had finished, the sum of the gravitational



Tube orbit switching to box orbit. Notice that the names describe the volume filled after a long time, and that the odd shapes arise because the orbits (unlike ones around a single point mass) do not precisely repeat. (Courtesy Tjeerd S. van Albada)

potentials of the stars in their orbits must add up to the one you had started with. This is unquestionably the right thing to do if the galaxies are made up entirely of stars. If most of the gravitation is due to dark matter, it may not be. In either case, the possible orbits are much more varied than mere conic sections. Some are banana-shaped (and avoid the center of the potential); others fill up boxes with curves that look like lissajous figures. Peanuts are also possible. The task of making the stars add up to the light and line profiles that you see, while remaining consistent with the potential you have chosen, is an on-going one.

AUX ARMES

Finally, no discussion of astrophysical asymmetries can be abandoned without mentioning spiral arms. They are ubiquitous in spiral galaxies (duh), and at least moderately frequent in other rotating gaseous disks, including those around stars in the process of formation and those around white dwarfs that are accreting gas from companion stars. Configurations with one, two, three, or four arms all happen. Twosies are the prettiest as well as the most common and are generally regarded as the norm. Physically arms are of (at least) two types. Some (called “grand design” in galaxies) are solitons, long lived, and mathematically interesting. Others (called “flocculent”

in galaxies) are transient and the analog of the single drop of cream dripped into rapidly rotating coffee in a cup. This works, by the way. I saw it for the first time this fall, with thanks to Mr. Merrick Berg of Astro 498N. Sometimes you can even see the wave reflect back off the side of the cup.

In galaxies, the role of the cup is played by the outer Lindblad resonance. There is also an inner Lindblad resonance (which is sometimes where bars in barred spirals end) and even two Lindblads, though both resonances are named for the elder, Bertil. They are resonances among sums and differences of three frequencies, that of rotation of the gas, that of rotation of the spiral pattern, and the epicyclic frequency at which a test particle in the disk will oscillate around its equilibrium position in the rotating coordinate system.

And, having listened to this much dynamics, you are entitled to another cup of coffee in which to try the drip-of-cream experiment. I would suggest red wine, but am not sure it is improved by cream. Oh well, yes, I have tasted wine that would be improved by a drop of gall and wormwood.

SOURCES AND ADDITIONAL WISDOM

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K. R. Lang, 1999, **Astrophysical Formulae**, 3rd Edition, now in two volumes, from Springer, is an excellent place to check on things like Lindblad resonances, Jacobi ellipsoids, and a usable expression for synchrotron radiation.

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The first Sunspot drawing is described by I. R. Stephenson and D. M. Willy in **Astronomy and Geophysics** (a publication of the Royal Astronomical Society) Vol. 40 (though it is only two years old), 6. 21.

The completely apocryphal Newton story was told by the late Raymond Arthur Lyttleton.