The Bones of Copernicus

Twenty-first–century cosmologists, historians and archaeologists continue to seek a true portrait of the great astronomer and his contribution

Dennis Danielson

In 2005 they dug up the remains of Nicolaus Copernicus. At least, they thought it was him, and they wanted to be sure. So the Polish archaeologists at work in the red brick cathedral in Frombork—where Copernicus had served as administrator and in his spare time hatched a new cosmology—turned to the police for help. Without divulging the name of the "victim," they sent the skull to the central forensic lab in Warsaw. And the resulting computer-enhanced reconstruction of a craggy 70-year-old man so closely matched Copernicus's own younger self-portrait that the researchers declared themselves 97 percent certain this was truly the face of the iconic astronomer. Even more recent evidence, based on DNA samples, suggests they were right.

But people have been probing Copernicus's remains for much longer than a few years. He is widely acclaimed as the founder of modern science—the first to get the ball rolling, almost literally. He proposed in the early 1500s that the sphere on which we live is not at the center of the universe but instead belongs to a class of round, rotating bodies known as planets, which circle about the Sun. Such are his prestige and fascination that for 400 years scientists have claimed him as a patron. Today, however, there appear to be fresh opportunities for discerning Copernicus's scientific legacy—along with his facial features—with enhanced clarity.

In the middle of the 20th century, astronomer Hermann Bondi evoked the image of Copernicus to support his and two Cambridge colleagues' steady-state cosmology. Bondi coined the term "Copernican principle" (CP) to sum up the idea that Earth "is not in a central, specially favoured position" in the universe. Since that time, the CP has continued to be endorsed by scientists even though steady-state cosmology has not.

In 1973, the year of Copernicus's quincentenary, Stephen Hawking and George Ellis published *The Large Scale Structure of Space-Time* and enlisted the Copernican principle to serve Big-Bang cosmology. The geometry of this expanding universe (on a large scale) is such that it would appear the same in all directions no matter where the observer is located. Thus was the Copernican denial of centrality appropriated by what has now become the Standard Model.

But Hawking and Ellis, rather than restricting themselves to an explication of cosmic geometry, openly admitted into their account of the CP what they called "an admixture of ideology":

> Since the time of Copernicus we have been steadily demoted to a medium sized planet going round a medium sized star on the outer edge of a fairly average galaxy, which is itself simply one of a local group of galaxies. Indeed we are now so democratic that we would not claim that our position in space is specially distinguished *in any way.* [emphasis added]

Yet today, emerging historical weaknesses in such sweeping interpretations of the CP, together with accumulating scientific objections to it, are causing some cosmologists to suspect that the CP may be about due for burial.

The "Privilege of Being the Center"?
The pervasive "pessimistic" interpretation of the Copernican principle, and of Copernicus generally, is growing frailer as scholars increasingly recognize that the astronomer and his followers did not themselves view Earth's "removal" from the center of the universe as a demotion. According to Aristotle, whose physical theory was the dominant one right into the 17th century, our sphere sat motionless at the center of the universe because earth (among the other elements: water, air and fire) was the heaviest of all substances—and the center of the universe was where heavy things settled. So it was simply Earth's heaviness, not its nobility or privilege, that accounted for the cosmic centrality of us Earth-dwellers.

Furthermore, writers of the Middle Ages and Renaissance interpreted that location as anything but an enthronement. The poet Dante in his *Inferno* famously depicted the lowest pit of hell as coinciding with the center of the Earth, which thus constituted the dead center of the whole universe. In 1486, in a work often considered a humanist manifesto, Italian philosopher Giovanni Pico referred to Earth as occupying "the excrementary and filthy parts of the lower world." In this prevalent view, therefore, the center was, in more ways than one, the pits. In 1568, a quarter century after the death of Copernicus, French philosopher Michel de Montaigne wrote that we are

> lodged here in the dirt and filth of the world, nailed and rivetted to

Dennis Danielson is an intellectual historian with interests in the scientific revolution and in the history, literature and cultural meaning of astronomy. His anthology of cosmological writings, The Book of the Cosmos, *was named to Amazon.com's Editor's Choice top 10 science books for the year 2000. His biography of Copernicus's sole student and "apostle,"* The First Copernican: Georg Joachim Rheticus and the Rise of the Copernican Revolution, *appeared in 2006. He has published in* American Journal of Physics, Nature, *and* Journal for the History of Astronomy, *and is head of the English Department at the University of British Columbia. Address: #397 – 1873 East Mall, University of British Columbia, Vancouver, BC, Canada V6T 1Z1. Internet: danielso@interchange.ubc.ca.*

Andreas Ehrhard/Alamy

Figure 1. In this portrait commemorating his 400th anniversary, Nicolaus Copernicus (1473–1543) is shown with his heliocentric model of the world. At right is a triquetrum, an instrument for measuring the altitudes of heavenly bodies. The Frombork Cathedral, where Copernicus's remains were found in 2005, is shown in the background. The oil-on-canvas painting was made in 1873 by Jan Matejko.

> the worst and deadest part of the universe, in the lowest story of the house, and most remote from the heavenly arch.…

Earth's centrality was thus seen much more as exile than enthronement. But Copernicus broke those bonds. The first account of any astronomical use of the telescope—Galileo's 1610 *Starry Messenger*—conveyed its author's excited realization that Earth (being a planet) is no longer

> excluded from the dance of the stars. For … the earth does have motion, … it surpasses the moon in brightness, and … it is not the sump where the universe's filth and ephemera collect.

Whereas Aristotelian-Ptolemaic cosmology had implied that the place of Earth was both low and lowly, Galileo could see that humanity's new Copernican perspective was, in more senses than one, uplifting, even uppity.

The other great Copernican of the early 17th century, Johannes Kepler, likewise saw Earth's new planetary position as a cosmic promotion. We could now imagine ourselves as making "an annual journey on this boat, which is our earth, to perform [our] observations.… There is no globe nobler or more suitable for man than the earth"—occupying, as it does, a place "exactly in the middle of the principal globes.… Above it are Mars, Jupiter, and Saturn. Within the embrace of its orbit run Venus and Mercury, while at the center the sun rotates.…" Only with the *abolition* of geocentrism, then, could we truly say that we occupied an optimal astronomical location.

The contrary, negative interpretation of Earth's "decentering," more familiar to us now, seems to have appeared for the first time in France more than a century after the death of Copernicus. Cyrano de Bergerac, though citing no actual evidence, associated pre-Copernican geocentrism with "the insupportable arrogance of Mankind, which fancies, that Nature was only created to serve it." Most influentially, French science popularizer Bernard le Bouvier de Fontenelle's *Discourse of the Plurality of Worlds* complimented Copernicus—who "takes the Earth and throws it out of the center of the World"—for knocking down "the Vanity of men who had thrust themselves into the chief place of the Universe."

This was the likeness of Copernicus embraced and reproduced by the Enlightenment and framed magisterially in 1810 by the German poet Johann Wolfgang von Goethe: "No discovery or opinion ever created a greater effect on the human spirit than did the teaching of Copernicus," for it obliged Earth "to relinquish the colossal privilege of being the center of the universe."

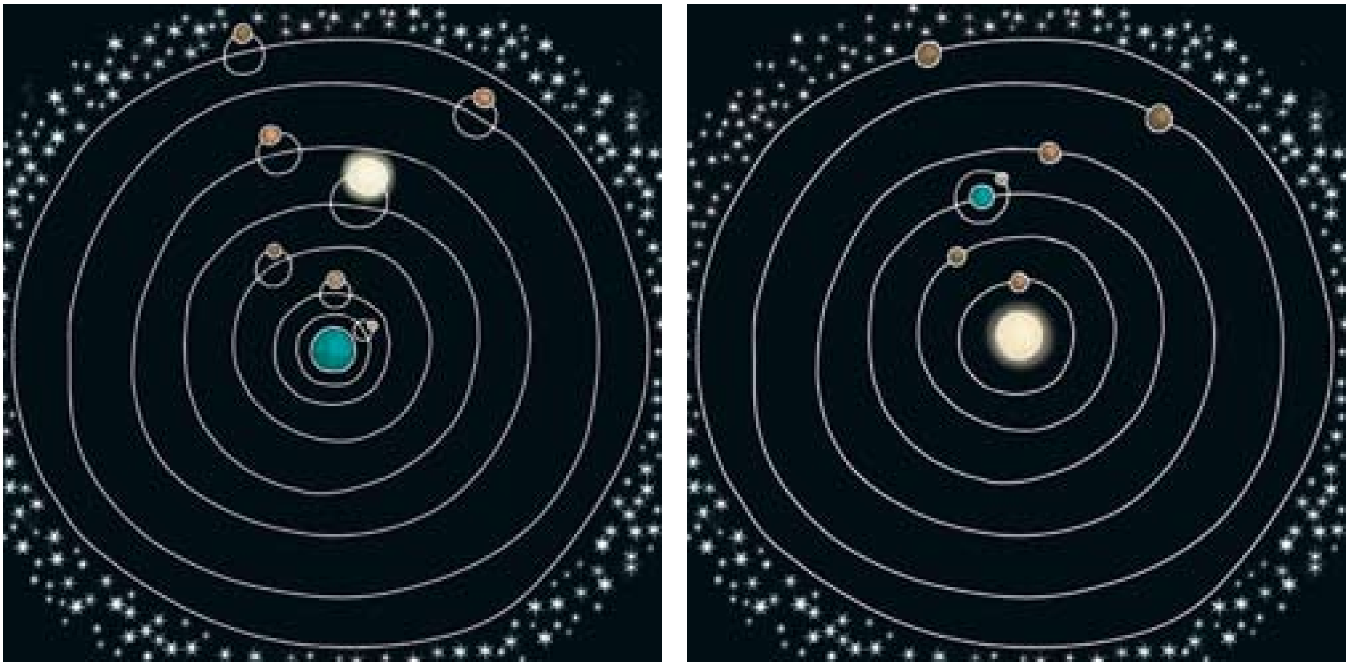


Figure 2. For centuries before Copernicus, a geocentric model of the world was favored *(left)*. In this Ptolemaic model, the planets (which include the Sun and the Moon) revolve around the Earth. In Copernicus's heliocentric model *(right)*, Earth joins the planets, which orbit the Sun. Although, over time, many came to view Earth's relocation as a demotion, its "decentering" was first seen in a more positive light. The small circular paths of the planets in the Ptolemaic model, called *epicycles*, were proposed to explain *retrograde motion*—the appearance that planets temporarily reverse direction. In the Copernican model, this phenomenon is explained as resulting from the changing mutual orientation of Earth and a given observed planet as each traces its orbit around the Sun.

Figure 3. Copernicus's ideas about the structure of the universe had been in limited circulation since the early 1500s. But his treatise on the subject, *De Revolutionibus orbium coelestium (On the Revolutions of the Heavenly Spheres)*, was not published until 1543, the year of his death. This title page is from the first edition. Courtesy of Octavo Corp. and the Warnock Library.

And this pessimistic, ideological portrait of Copernicus is the one still endorsed by a majority of educators and scientists today. Even thoughtful cosmologists such as Paul Davies of Arizona State University continue to assert that the Ptolemaic, geocentric model represented humankind—by "a natural corollary"—as "the pinnacle of God's creation," and accordingly that Copernicus carried out our cosmic demotion.

Yet it is increasingly clear that reasonable people need not accept this picture—and that those who want to continue propagating it must offer more by way of support than mere "admixtures of ideology" and stale 200-year-old assumptions. The historical record amply suggests, as University of Alberta cosmologist Don Page puts it, that

> the Copernican revolution itself did not necessarily demote humans from a privileged position at the center of the universe but often was interpreted as exalting humans from the dump heap at the bottom to a more heavenly position on a planet.

Perfect vs. Special

But what today is the status of the principle, rather than the portrait, that for more than half a century many scientists have associated with the name of Copernicus? To get some up-to-date answers, I asked a selection of active cosmologists and astronomers for their take on what is so often blithely passed off as textbook fact. The following discussion incorporates a range of their responses, which proved surprisingly diverse.

On at least one point there appears to be relative scientific agreement: Almost everyone now rejects a particular notion that earlier, steady-state theorists associated with the Copernican principle. Bondi not only asserted that the universe would look the same irrespective of an observer's location in space; he also proposed a "perfect cosmological principle" whereby "the universe presents the same aspect from any place *at any time*" [emphasis added]. More and more features of the Standard Model have conspired to shatter that cosmologically uniformitarian, steady-state dream of temporal perfection.

Harvey Richer, stellar astronomer at the University of British Columbia and an expert on the age of the universe, cites evidence that certain kinds of galactic evolution were required before life forms could appear and be supported. "For example," he says, a certain level of heavier elements was necessary, and these are produced in stars over extended periods of time. So we could not have been "here" many billions of years ago.

The specialness of our own epoch is also indicated by a look into the future. Virginia Trimble of the University of California, Irvine, another stellar astronomer, points out that many galaxies, including our own, face a "last gasp" problem: "The current supply of gas won't sustain the current star formation rate for very long." She notes that "there used to be a sort of 'that's not Copernican' tendency to say that infalling primordial gas would keep up the supply for another 10 or 15 billion years at least, so that 'now' is average." But because "the star formation rate really has been dropping monotonically for the last half or so of the age of the universe," concludes Trimble, we "do live in a somewhat special time." For the processes we once counted on to ensure galactic sustainability are truly "past their prime."

In case the perfect cosmological principle of Bondi and the steady-state theorists required any further nails in its coffin, physicists Lawrence Krauss of Arizona State University and Robert Scherrer of Vanderbilt recently published, in the journal *General Relativity and Gravitation*, a sobering study probing conditions a hundred billion years in the future. If there are observers, the authors note, they will still be able to inspect our own galaxy, because it is gravitationally bound. But given the accelerating expansion of the cosmos overall, other galaxies will have receded from view, and the cosmic background radiation will likewise be unobservable.

So in that distant future, cosmic expansion itself will have absconded with all the fossils that today allow us to trace the archaeology of our universe. Krauss and Scherrer thus predict "the end of cosmology." Ironically, then, for inhabitants of the extrapolated far-future state of the cosmos, the very expansion that keeps us from believing in a static universe will be invisible and so leave them no alternative to "the standard model of the universe c. 1900." In such a model, the galaxy *is* the universe. With the chief signs of cosmic evolution thus obscured, the illusion of transtemporal stasis just might return with a vengeance.


ΣΕΛΗΝΑΡΧΙΑ

ΣΕΛΗΝΑΡΧΙΑ. OR, THE GOVERNMENT Of the WORLD In the MOON: A COMICAL HISTORY. Written By that Famous Wit and Cavalier of France, Monsieur Cyrano Bergerac: And Done into ENGLISH By THO. S'SERF, Gent.

LONDON, Printed by J. Cottrel, and are to be sold by Hum. Robinson at the three Pigeons in Pauls Churchyard. 1659.

Figure 4. In 1657 French dramatist Cyrano de Bergerac's *L'Autre monde ou les états et empires de la Lune* appeared. Thomas St. Serfe translated it into English as *Selenarchia: The Government of the World in the Moon, a Comical History* in 1659. This edition's frontispiece *(above)* depicts Cyrano being lifted heavenward by "bottles of dew" heated by the Sun. In this work of proto–science fiction, Cyrano offered an early instance of a negative view of Earth's repositioning in the heliocentric model. Copernicus, he suggested, had corrected humankind's "arrogance"; Earth was now put in its place. Courtesy of Perkins/Bostock Library, Duke University.


SIDEREVS NVNCIVS MAGNA, LONGEQVE ADMIRABILIA

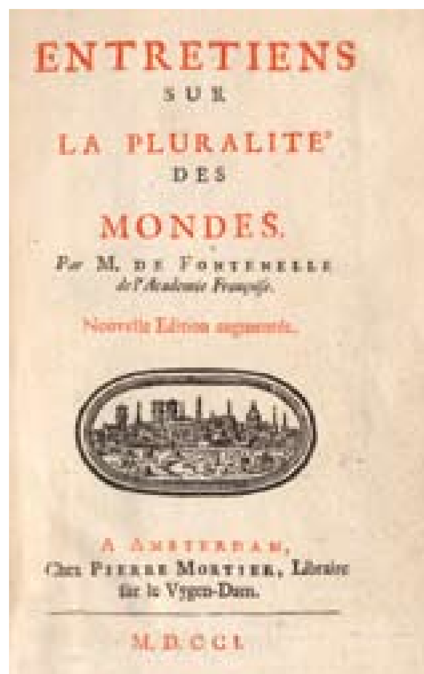
GALILEO GALILEO PATRITIO FLORENTINO

PERSPICILLI

QVATVOR PLANETIS

MEDICEA SIDERA NVNCVPANDOS DECREVIT.

VENETIIS, Apud Thomam Baglionum. M DC X.


ENTRETIENS SUR LA PLURALITE' DES MONDES. Par M. DE FONTENELLE de l'Academie Françoise. Nouvelle Edition augmentée.

A AMSTERDAM, Chez PIERRE MORTIER, Libraire sur le Vygen-Dam.

M.DCCI.

Figure 5. Galileo's *Sidereus Nuncius (Starry Messenger)* appeared in 1610 *(left)*. In it, Galileo expressed delight that in the heliocentric model Earth, as a planet, is no longer "excluded from the dance of the stars." Bernard le Bouvier de Fontenelle offered a grimmer picture 76 years later in his *Entretiens sur la Pluralité des Mondes*, or *Discourse of the Plurality of Worlds (1701 edition at right)*. He called it "vanity" to consider Earth the center of the universe—and suggested that Copernicus accurately implied Earth's lack of importance. Image at left courtesy of Octavo Corp. and the Warnock Library; image at right courtesy of the University of Chicago Library Special Collections.

Linda Hall Library of Science, Engineering & Technology

Figure 6. Andreas Cellarius's *Atlas Coelestis seu Harmonia Macrocosmia*, first published in Amsterdam in 1660, presented stunning visual depictions of cosmological theories. This detail from the frontispiece of a 1661 reprint, engraved by Frederik Hendrik van den Hove, shows Copernicus contemplating his model of the solar system. In addition to Copernicus's ideas, the *Harmonia Macrocosmia* includes models proposed by Ptolemy and Tycho Brahe. Cellarius's intricate maps and star charts remain among the most celebrated of his time.

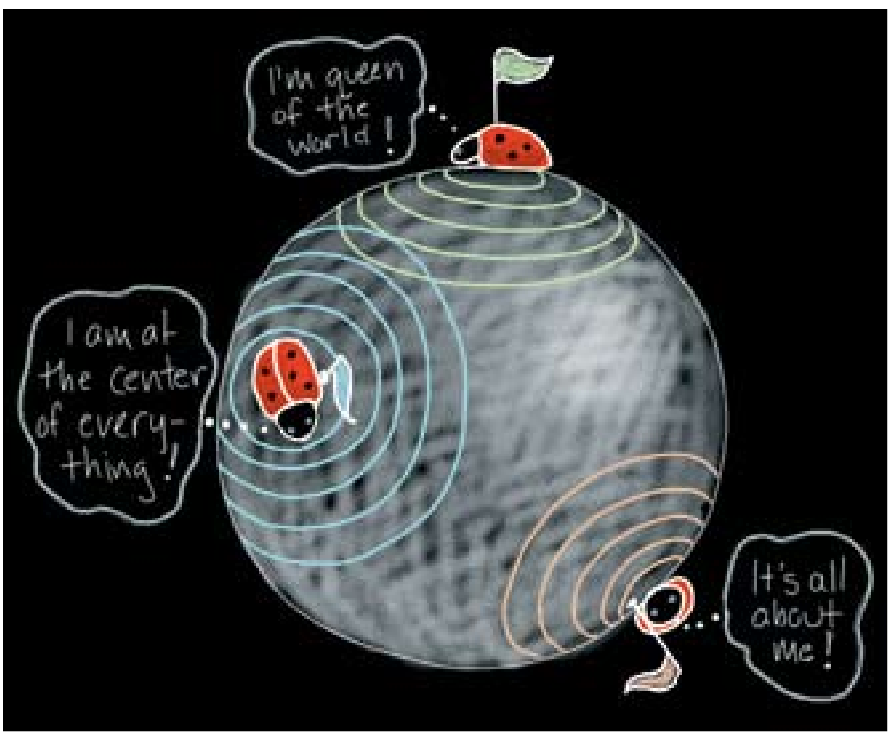


Figure 7. Each of a number of ladybugs crawling on a perfectly round beach ball might perceive that she is at the center of the ball's surface. This surface, or "space," is isotropic; geometrically, it has uniform positive curvature. But the bugs' perceptions are only partially correct: Although each can claim to be at the center, there is no *unique* center. Thus, in addition to entailing each ladybug's apparent centrality, isotropy supports the *principle of mediocrity*, which states that geometrically *every* point in space behaves as if it were the center.

For now, though, given the evidence arrayed before us, any large-scale temporal homogeneity is apparently a non-starter. From a chronological perspective, we do indeed dwell somewhere near the center—in what increasingly looks like a cosmological golden age. As Krauss and Scherrer conclude,

> We live in a very special time in the evolution of the universe: the time at which we can observationally verify that we live in a very special time in the evolution of the universe!

Muddles about Mediocrity

Moving from time to space, we also find considerable unanimity regarding the geometry associated with the Copernican principle. Copernicus famously declared that "there is more than one center," something Galileo confirmed observationally when he raised his telescope to the heavens and discovered four "Medicean stars" circling Jupiter. But today's cosmologists go further, asserting both that there *is* no (unique) center and that *everywhere* is the center. How can this be?

As University of Texas Nobel laureate Steven Weinberg points out, the Copernican principle harmonizes with the space-time geometry implied by the Robertson-Walker metric, which describes a spherical universe in four dimensions. The simplest analogy is a three-dimensional sphere—like a perfectly round beach ball—on whose surface ladybugs are located at different points. The ball's surface is their "space."

Any one of these bugs might think she is located at the center of her space, because her spatial environment displays the same geometrical features in all directions; it is *isotropic.* And in one sense, she'd be right, because in whatever direction she measures, she finds herself equidistant from the farthest limit of her space. Yet if she claimed her particular spot as *the* center, we'd tell her she's naive, because we know the measurements taken by other bugs elsewhere on the ball will produce exactly the same results.

In the Standard Model universe every point in space likewise behaves, geometrically, as if it were the center. Not only is this claim—often called the *principle of mediocrity*—consistent with the Copernican principle's assertion that there is no unique center, but in fact one proposition is the flipside of the other. On the beach ball, each bug's observations *seem* to be made from a central point of view; but from a larger perspective, each location is understood to be not so much central as mediocre, or merely typical—something that follows from the isotropy and homogeneity of the "universe" it inhabits.

The claim that spatially our universe is isotropic and homogeneous is known as the *cosmological principle*. According to Jim Peebles of Princeton, one of the modern pioneers of physical cosmology, it "was introduced as a philosophical/ad hoc/working assumption"—an assumption, Peebles suggests, "which maybe illustrates the influence of the Copernican principle." But by now, he says, "the observations have spoken" and the cosmological principle "is a done deal."

The cosmological principle is thus the least problematic among the trio of principles mentioned here. Its very name embodies truth in advertising: It is about cosmology, and its payload is unambiguously geometrical and scientific. The other two, by contrast, seem to invite divergent scientific interpretations. When asked what they see as the relationship between the Copernican principle and the principle of mediocrity, Paul Davies replies that he "uses them synonymously"; Wendy Freedman, director of the Carnegie Observatories in Pasadena, California, simply answers, "None."

A still greater problem with the Copernican principle as well as the principle of mediocrity is the nonscientific inferences draw from them by both scientists and others. As already mentioned, since the mid-1600s the legacy of Copernicus frequently has been appropriated to serve a misanthropic agenda. Add to this tendency the potential ambiguity, even insult, of phrases like "mediocre," "not special" and "not privileged," and it's little wonder that scientific rigor is often shrouded by amateur philosophizing. Even standard textbooks such as Edward Harrison's *Cosmology* present humankind's "renunciation of cosmic privilege" as being driven by the march of science.

Does Size Matter?

Yet suppose we restrict the Copernican principle and its geometrical, "mediocratic" twin to their scrupulously scientific roles. Isn't it still true that Copernicus and the process he started rendered Earth and its inhabitants depressingly minuscule relative to the size of the universe?

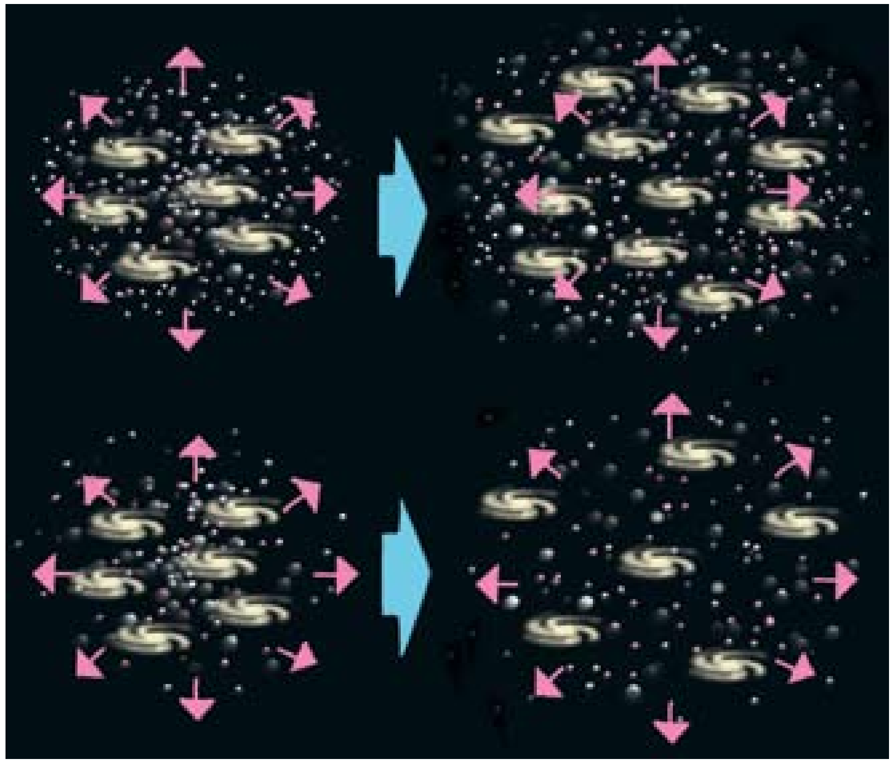


Figure 8. Steady-state cosmology *(upper diagram)* is now rejected by the majority of cosmologists. It describes an apparently expanding universe that is homogeneous and isotropic both spatially and temporally. To account for this, it suggests that as the galaxies recede from each other, new matter spontaneously emerges to fill in the gaps. The now-accepted Standard Model *(lower diagram)* rejects the time component of steady-state theory, declaring nonetheless that, when observed from any given point in space, the universe is homogenous and isotropic.

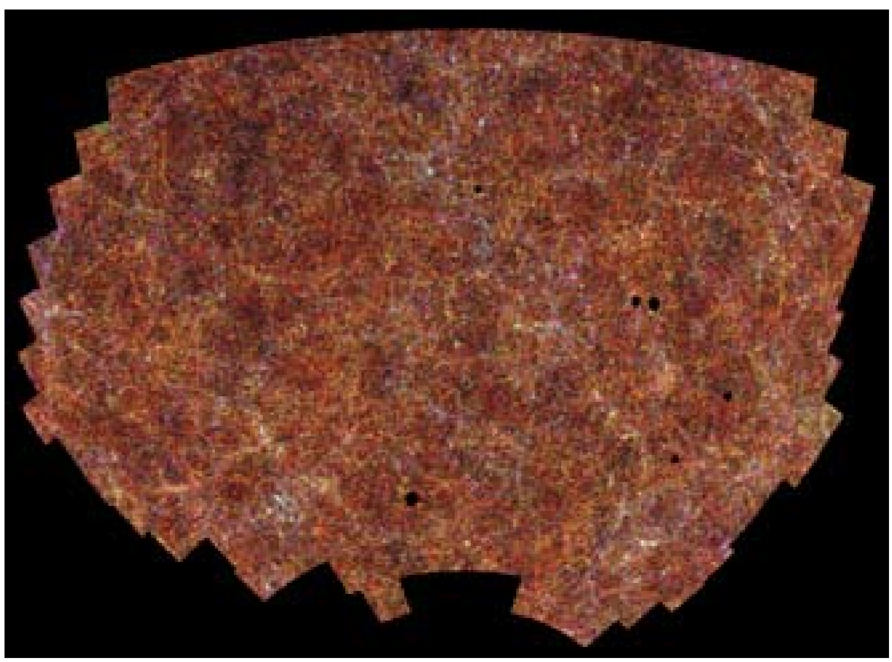


Figure 9. The cosmological principle is illustrated on a vast scale by this scan of about 3 million galaxies recorded by the Automatic Plate Measuring machine at the Institute of Astronomy in Cambridge. The image shows those galaxies' distribution as a density map in equal-area projection on the sky. Each pixel covers a patch of sky 0.1 degrees square, and its brightness indicates the concentration of galaxies within the area. Red indicates fainter galaxies, green areas are of intermediate brightness, and blue represents the brightest. Bright stars and other bodies that would interfere with the rendering are shown in black. Although the distribution of galaxies varies, a survey of this scope reveals the overall homogeneity of the universe. Image courtesy of Steve Maddox, University of Nottingham.

Figure 10. Some current views of our place in the universe offer a cheerier picture than the one that has emerged since Cyrano's denunciations. As Jaymie Matthews notes, recent observations suggest that the stuff required for life to emerge is so rare that, rather than being the "flour" in the "cosmic recipe," we are more like the spices. Since the 1500s, we've gone from considering ourselves the "sump" of the universe to being its salt and pepper—not bad after all.

Linda Hall Library of Science, Engineering & Technology

Figure 11. On the title page of John Wilkins's *A Discourse Concerning a New World and Another Planet* (1640 edition), Galileo and Kepler *(right)* support the picture of the world proposed by Copernicus *(left).*

Copernicus's affirmation that the Earth's orbit is immeasurably small in relation to the size of the sphere of the "fixed stars" entailed an enlargement of the volume of the universe by no less than nine orders of magnitude. And that was before telescopic astronomy got going with its relentless unfolding of immensities. So it's no surprise if an experienced astronomical all-rounder like Jay Pasachoff of Williams College concludes, "I don't think that Earth or humankind has any special significance in the cosmos." Peebles waxes poetic in the same dark vein: "We are exceedingly minor insignificant debris—a little dust—in the grand plan of nature."

However, some scientists are voicing caveats against such humanly pessimistic readings of the history of cosmology. In words that might have cheered Copernicus himself, Freedman asserts that "there is a difference between being in a significant place and accomplishing something significant." We may be nothing great "on the scale of the cosmos," she says, "but the fact that a species developed the curiosity to look out into space and ask these questions is highly significant."

Such rethinking of the cosmic role of Earth and its inhabitants is being fueled by three powerful trends in cosmology, all of them related directly to issues of the scale or mass of the universe. The most obvious trend, as already hinted at by Richer, is to recognize that we couldn't be here unless the universe were as big, and therefore as old, as it is. So there's no point bewailing our smallness relative to the immensity of the cosmos when our very existence is predicated on those staggering proportions.

Then there's the growing recognition of how cosmically *a*typical is the stuff we're made of. Recent estimates put baryonic matter—the atoms that make up galaxies, stars and humans—at no more than 5 percent of the mass of the universe (after dark energy and dark matter). Exoplanet hunter Jaymie Matthews of the University of British Columbia reflects that

> only three decades ago we believed we were composed of the basic primordial ingredients of the universe—the flour of the Cosmic Recipe. Now we are considered the condiments, or possibly (I would like to think) the spices.

He adds, "Does that make us insignificant? Only if you would prefer to dine in a world where spices don't exist."

Thus the "argument from size" can cut both ways. Superficially, the larger the universe is, the smaller and less significant we worry we are in relation to it. Yet the larger the universe is, and the more of it that's too hot, too cold or otherwise hostile to life, the more exceptional, rare and special do our Earthly habitat and conscious existence appear to be.

A third trend is concerned less with the rarity of our place or our existence than with the specialness—the fine tuning—of the observable universe as a whole. So great appear the odds against a cosmos in which (for example) stars can form, and thus provide the prerequisites of carbon-based life, that many cosmologists are proposing an astonishing number, perhaps an infinitude, of other possible or even actual universes. At least part of their motivation for these "multiverse" scenarios is the desire to come up with a number large enough to even the odds against such a mind-bogglingly special universe as ours is.

So even if we grant that life may exist elsewhere in our universe, reasons Don

Page, it is still quite possible that life itself is cosmologically "special, since it might occur only in a tiny fraction of the universe or multiverse." In any case, why should serious minds accept those slogans trying to tell us that bigger is better? Surely, as Page says, "most people would recognize that size alone, or fraction of the universe occupied by life, is not that important."

One Resurrection and a Funeral

Where does all this leave Copernicus and the Copernican principle? The simple answer is: not necessarily in the same place.

Copernicus achieved the great things he did because he sought beauty in the structure of the world; he wasn't satisfied with mere models that "saved the appearances" (he wanted to know how the universe *really* works); he expected nature and mathematics to agree; and he realized that the location, movement and participation of observers must be taken into account if we're seeking a scientifically coherent picture of the cosmos.

Many of the items on today's cosmological agenda—string theory, inflation, anisotropy probes, discussions of the multiverse, anthropic selection effects and more—are supported and guided by those robust Copernican impulses. To this extent, Copernicus is alive and with us still.

The *cosmological* principle remains healthy, though it might be even healthier if cut loose from its alter ego which bears the same "CP" insignia. The principle of mediocrity too might usefully survive, though only if restricted to the one thing it's really good at: cosmological geometry. The Copernican principle itself, however, is in serious trouble. Page calls it "a working hypothesis that is being abandoned if taken in its original strict meaning."

Others would like to pronounce it dead already. MIT's Max Tegmark is among the most willing to offer an obituary. Asked for his assessment of the CP, he replies simply that it is "incorrect and belongs in the dustbin of history." Citing various broad parameters of specialness and fine-tuning already mentioned, he argues that

> it is manifestly incorrect even in the part of space that we can observe (we live in a galaxy rather than an intergalactic void, on an unusually habitable planet, on its surface rather than in its more voluminous interior, etc.).

The Copernican principle's sole remaining value, declares Tegmark, is, "as an example of how even very smart scientists can go wrong."

So it is abundantly clear that at least some are ready to bury its bones. Adds Tegmark, as if this whole chapter of cosmology might be wrapped up in a single text message: "CP RIP."

Acknowledgments

Sincere thanks to Paul Davies, George Ellis, Wendy Freedman, Owen Gingerich, Lawrence Krauss, Jaymie Matthews, Don Page, Jay Pasachoff, Jim Peebles, Martin Rees, Harvey Richer, Leonard Susskind, Max Tegmark, Virginia Trimble and Steven Weinberg.

References

Bondi, Hermann. 1952. *Cosmology.* Cambridge: Cambridge University Press.

Carr, Bernard, ed. 2007. *Universe or Multiverse?* Cambridge: Cambridge University Press.

Danielson, Dennis R. 2000. *The Book of the Cosmos: Imagining the Universe from Heraclitus to Hawking.* Cambridge, MA: Perseus Books.

Danielson, Dennis R. 2001. The great Copernican cliché. *American Journal of Physics* 69:1029–1035.

Davies, Paul. 2007. *Cosmic Jackpot: Why Our Universe is Just Right for Life.* Boston: Houghton Mifflin.

Ellis, George F. R. 2007. Issues in the philosophy of cosmology. In *Philosophy of Physics*, ed. Jeremy Butterfield and John Earman, pp. 1183–1283. Amsterdam: Elsevier.

Gingerich, Owen. 2006. *God's Universe.* Cambridge, MA: Harvard University Press.

Goethe, Johann Wolfgang von. 1802. *Materialien zur Geschichte der Farbenlehre.* In *Goethes Werke.* Hamburg: Christian Wegner Verlag.

Harrison, Edward. 2000. *Cosmology: The Science of the Universe.* 2nd edition. Cambridge: Cambridge University Press.

Hawking, Stephen, and George Ellis. 1973. *The Large Scale Structure of Space-Time.* Cambridge: Cambridge University Press.

Krauss, Lawrence, and Robert Scherrer. 2007. The return of a static universe and the end of cosmology. *General Relativity and Gravitation* 39:1545–1550.

For relevant Web links, consult this issue of *American Scientist Online:*

http://www.americanscientist.org/issues/id.76/past.aspx