ASTRONOMY

Celebrating the 400th Anniversary of Telescope Astronomy

Since Galileo looked skyward 400 years ago, telescopes have evolved to provide a broader and deeper understanding of the universe.

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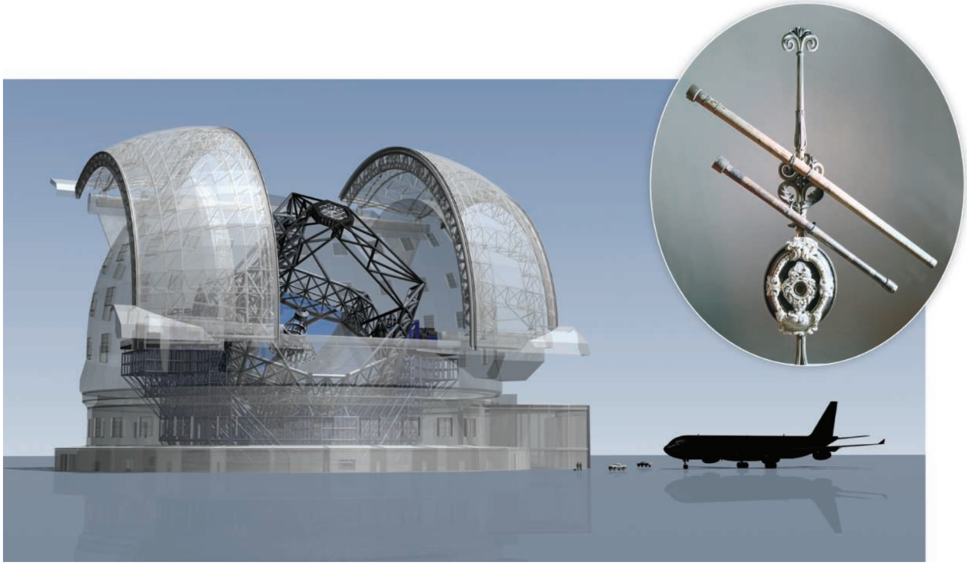
Science authors laboring under the oppressive yoke of refereeing should think back to the time when Galileo Galilei brought his manuscript to printer Baglioni in Venice at the end of February 1610. The referee for his *Sidereus Nuncius*—a short treatise based on his first observations made through a telescope—was to be the office of the Holy Inquisition. Galileo knew that those referees didn't simply reject what they didn't like: They might invite you in for a few questions. But that time he was in luck. On 1 March, the Venice Council, on advice of the local Inquisitor, gave its consent.

Few know that Galileo (and Baglioni) then took an astonishing risk. Such was his passion for his new telescope that Galileo added observations and comments dated up to 2 March—materials that the Inquisitor could not possibly have seen. But those last few additions are so beautiful. For the first time since 7 January, when Galileo had started observing Jupiter, a "fixed" star had entered the small field of view of his instrument. As he kept pointing to the planet and its twirling satellites, the star appeared to move steadily across, as apparent in his sketches dated 27 February to 2 March. This provided conclusive proof that Jupiter carried these satellites (moons) in its motion against the background sky: a finding that would have definitely risked the Inquisitor's wrath.

By this time, Galileo must have been really busy—finalizing text, checking proofs and figures, a real headache these, especially the famous Moon plates from his earlier 1609 observations. Half-tones had to be hand-etched in wood by one of Baglioni's artists, who had Galileo's beautiful water colors in front of him. Probably hard-pressed, the etcher made a poor job of it. Luckily, however, the originals have survived, revealing the gifted hand of a true son of the Florentine renaissance. They can be admired, along with countless other galileiana, in Florence at the Palazzo Strozzi Exhibition (*1*).

By 13 March 1610, 550 copies of the *Sidereus Nuncius* were ready to document a brave new era, that of astronomy with a telescope. Bigger and better telescopes were soon invented by Isaac Newton (born 1642, the year of Galileo's death), Gian Domenico Cassini (1625 to 1712), and innumerable others to follow, giving mankind an ever-growing universe: from solar system to stars, from stars to our Galaxy, and from there to an expanding universe full of as many galaxies as there are stars in our own, about 100 billion.



Telescopes past and future. An artist's impression of the European Extremely Large Telescope, planned to have an imaging mirror in excess of 40 m in diameter. The inset shows the telescope used by Galileo to make his astronomical observations of the night skies from 1609 onward.

In the past 400 years, telescopes have also evolved the capacity to tell us what stars are made of, allowing us to learn that our own bodies (and all we see) have been made by stars. True, the ignition of the first stars in the universe, about 13 billion years ago, has not yet been recorded, but we are working on it. The European Extremely Large Telescope (E-ELT) (*2*), for example, should do the job. With its mirror diameter exceeding 40 m (compare with the 4-cm Galileo lens), the E-ELT will be close to the extreme of what we are currently able to realize and afford for observations at optical wavelengths. But astronomers are also planning a Square Kilometre Array of radio telescopes (*3*), the ultimate challenge in astronomy with radio waves. These large, steerable antenna dishes have detected, for example, radio pulsars, stars that pack the mass of our Sun in a wildly rotating 10-km sphere.

Over the past 40 years, we have been putting telescopes in space for an "astronomy of the invisible" that would have challenged Galileo's comprehension. It's hard to describe as telescopes the Geiger-counter–based contraptions that Riccardo Giacconi and colleagues put in a rocket nose in 1962. Yet, they gave us a glimpse of our first cosmic x-ray sources. Today's state-of-the art orbiting x-ray telescopes have huge photon-focusing optics and will soon log half-a-million x-ray sources in the sky. Among these sources are accreting black holes, objects with exotic physics.

Ten years after x-ray astronomy, gamma-ray astronomy was born. Gamma-ray photons are impossible to focus, so it's much harder to build effective gamma-ray telescopes. Still, mostly thanks to the recently launched Fermi Gamma-ray Space Telescope (*4*), thousands of gamma-ray sources in the sky will be pinpointed. Some of them, such as Geminga-like neutron stars, are only "visible" in the gamma-ray region of the spectrum. So, too, are the 5000 mysterious "gamma-ray bursts." Because these bursts are fantastically energetic, cosmological one-time events, special telescopes have had to be invented.

Even more discoveries have come from telescopes in space: numerous infrared and ultraviolet stars and galaxies, many observed by the Hubble Space Telescope (*5*)—the most productive astronomy machine ever. Yet

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another telescope in space imaged the baby universe when it was only 300,000 to 400,000 years old and just twice the size of our Galaxy. At that age, it is visible only at microwave wavelengths, expansion-cooled from Big-Bang temperatures. Those cosmological photons carry, imprinted in their tiny fluctuations, the whole of today's universe.

What telescopes can we expect for the future? Galileo and Newton would go for the unknown. The still truly unknown in the universe is its nonelectromagnetic content—neutrinos and gravitational waves. We know that gravitational waves exist, and we know the theory behind a telescope for catching them, but we've yet to detect them with the likes of the Laser Interferometer Gravitational-Wave Observatory. In contrast, neutrinos have been observed, both from our Sun and from a local supernova, using underground detectors as our telescopes.

Neutrino astronomers are, I believe, on the brink of important discoveries. Some now use Earth as a detector, including its Antarctic ice (the IceCube project) or ocean water (the ANTARES project) (*6*, *7*). It is difficult to imagine a bigger telescope, yet it matches the elusiveness of its target. These telescopes—like the E-ELT, the Square Kilometre Array, and the future space telescopes—are worthy descendants of Galileo's *specillum*, and still look at the same sky.

References

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MICROBIOLOGY

Getting in Touch with Your Friends

Christopher J. Marx

Evolution of complex physical interactions between microbes promotes growth and enables behaviors that neither party can perform alone.

Microbes use a broad palette of chemical transformations to harvest energy and nutrients, but they do not always accomplish these conversions on their own. Particularly in anaerobic environments, various metabolisms are stimulated by, or depend upon, partnerships (*1*). In this form of interaction—termed syntrophy—one organism typically converts the primary resource to an intermediate that can be used by a partner (which perhaps passes it along to the next, and so on). In other cases, one partner may use a resource and provide a different type of service in return, such as a trace vitamin or motility. Recent studies are beginning to shed light on the mechanisms by which such partners communicate and interact and on how such interactions emerge in the first place.

Recently, a novel interspecies signaling mechanism was found (*2*) between two syntrophic partners present in high-temperature anaerobic sewage digesters: the bacterium *Pelotomaculum thermopropionicum* strain SI and the methanogenic archaeon *Methanothermobacter thermautotrophicus* strain ΔH. *P. thermopropionicum* can ferment propionate to acetate, bicarbonate, and three H_2 molecules, but this conversion is highly endergonic ($\Delta G° = 76.1$ kJ mol^{-1}). Propionate oxidation can proceed if the partial pressure of H_2 is kept low by *M. thermautotrophicus*, which consumes four H_2 molecules for every CH_4 produced (combined $\Delta G° = -25.6$ kJ mol^{-1}). This interaction provides an energy source to *M. thermautotrophicus* while enabling propionate oxidation by *P. thermopropionicum*.

When grown together, these two strains form aggregates that are held together by the flagellum of *P. thermopropionicum* (*3*). The average distance between cells of each species needed to achieve the observed growth rate is just 2 µm (see the figure, panel A). Shimoyama *et al.* (*2*) have uncovered an additional role for flagellum adherence: an interspecies signal that stimulates methanogenesis in *M. thermautotrophicus* (see the figure, panel B). The flagellar tip protein (FliD) from *P. thermopropionicum* induced widespread changes in gene expression in *M. thermautotrophicus*, including transcripts encoding hydrogenases and many of the enzymes of methanogenesis. In *M. thermautotrophicus* monocultures, stimulation by FliD led to a sharp increase in the rate of H_2 use, and hence CH_4 formation. Given that FliD adherence was only found with two methanogens across 21 genera screened, this appears to be a fairly specific, but not unique, characteristic of this pair.

This flagellum-dependent communication system differs from other known interspecies signaling systems (*4*) in that it is not mediated by a small molecule or peptidoglycan, but rather by a protein constituent of a cellular appendage. In this regard, the system resembles within-species recognition, for example, in slime mold (*5*), yeast (*6*), and the bacterium *Proteus mirabilis* (*7*). In these systems, recognition via shared surface loci is relevant for partner recognition and mediates multicellular behaviors such as forming a fruiting body, flocculation, and the formation of swarm boundaries, respectively. It may be that nondiffusible signals such as appendages are preferable for associations in which the partners must be arranged within a few micrometers to function optimally.

Perhaps the most intricate, highly developed microbial consortium thus far identified is the pairing known as "*Chlorochromatium aggregatum*" (*8*). This assemblage contains a single, motile β-proteobacterium (central bacterium) encrusted with a layer of nonmotile photosynthetic green sulfur bacteria (epibionts) (see the figure, panel C). Rather than overcoming thermodynamic constraints, the driving force for this consortium appears to be behavioral: The nonmotile photosynthesizers hitch a ride on their partner to move to their optimal depth in stratified lakes (no O_2, plenty of H_2S, and light of a wavelength matching the absorption maximum of their pigments). The photosynthesizers appear to pay their fare through supplying the central heterotroph with fixed organic carbon. Wanner *et al.* (*8*) have reported evidence for specialized attachment structures at the point of contact of each photosynthesizer with the central cell; furthermore, periplasmic tubules extending from the central bacterium appear to generate a continuous periplasmic space between all partners (see the figure, panel D). Well-developed signaling mechanisms—perhaps mediated by surface structures—probably also underlie this partnership.

From an evolutionary perspective, these sophisticated symbioses illustrate two very different classes of interactions. In *C. aggregatum*, there appears to be reciprocation of two costly

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