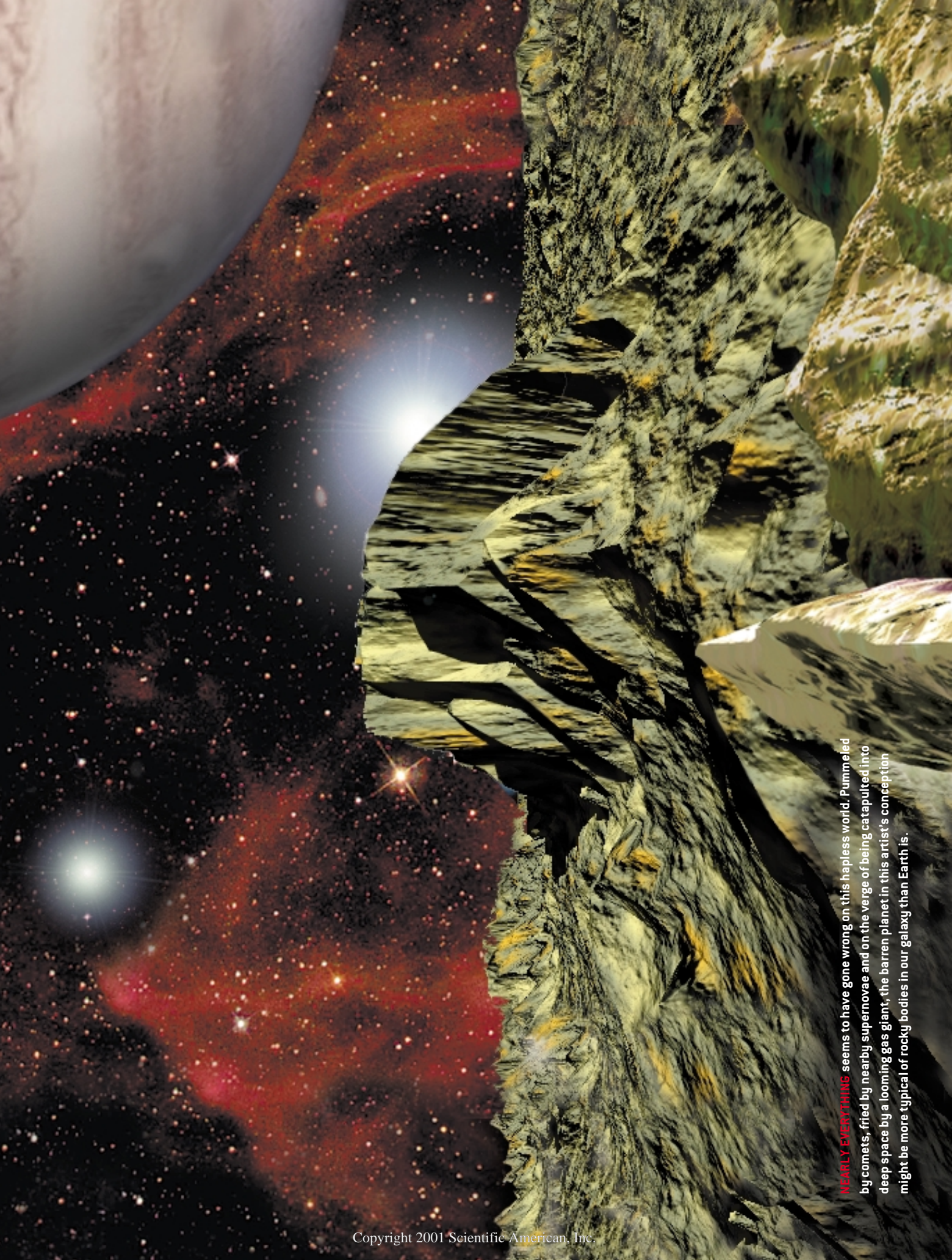


Only part
of our galaxy
is fit for
advanced life

Refuges for Life in a

Hostile Universe

By Guillermo Gonzalez,
Donald Brownlee
and Peter D. Ward



NEARLY EVERYTHING seems to have gone wrong on this hapless world. Pummelled by comets, fried by nearby supernovae and on the verge of being catapulted into deep space by a looming gas giant, the barren planet in this artist's conception might be more typical of rocky bodies in our galaxy than Earth is.

In science-fiction stories, interstellar travelers visit exotic locales in the Milky Way and meet with interesting aliens. You name the place, and someone has put a civilization there: the galactic center, a globular cluster, a star-forming region, a binary star system, a red dwarf star. Part of the reason that sci-fi writers have

to be so inventive is that scientists keep spoiling the fun. It used to be quite respectable to speculate about intelligent beings on the moon, Mars, Venus, Jupiter or even the sun, but nowadays canal-building Martians and cool oases inside the sun are merely quaint notions. As writers go ever farther afield to situate their characters, scientists are not far behind. Researchers are now casting a skeptical eye on musings about the prevalence of intelligent life throughout the Milky Way. Just as most of the solar system is hostile to multicellular organisms, the same may be true of much of the galaxy.

Within a given planetary system, astronomers describe the optimal locations for life in terms of the circumstellar habitable zone (CHZ). Although its definition has varied, the CHZ is generally considered to be the region around a star where liquid water can persist on the surface of a terrestrial, or Earth-like, planet for at least a few billion years. The zone is ring-shaped [see illustration on opposite page]. Its inner boundary is the closest that a planet can orbit its host star without losing its oceans to space. In the most extreme case, a runaway greenhouse effect might take hold and boil off the oceans (as happened on Venus). The outer boundary is the farthest a planet can roam before its oceans freeze over. From basic stellar theory, astronomers can estimate the size of the CHZ for a star of any mass [see “How Climate Evolved on the Terrestrial Planets,” by James F. Kasting, Owen B. Toon and James B. Pollack; SCIENTIFIC AMERICAN, February 1988].

Obviously, many other factors also contribute to the hab-

itability of a planet, including the ellipticity of its orbit, the company of a large moon and the presence of giant planets, let alone the details of its biology. But if a planet orbits outside the zone, none of these minutiae is likely to matter. Similarly, it doesn't make much difference where the CHZ is located if the planetary system as a whole resides in a hostile part of the galaxy.

Thus, in 1999 we proposed the concept of a galactic equivalent to the CHZ: the galactic habitable zone (GHZ). The GHZ defines the most hospitable places in the Milky Way—those that are neither too close nor too far from the galactic center. We are not the first to consider habitability in this broader context. For the past decade Virginia Trimble of the University of Maryland and the University of California at Irvine has been writing about the connection between galactic chemical composition and the conditions required for life. But in recent years, there has been a huge breakthrough: the discovery of giant, Jupiter-size planets around sunlike stars. Not every sunlike star has such a planet. In fact, the giant planets discovered to date are primarily found around stars that are rich in chemical elements heavier than helium—what astronomers call “metals.” This correlation suggests that metal content is an important factor in forming giant planets. (At present, the leading search technique cannot detect Earth-size planets.) At the same time, astronomers have gained a new and sobering appreciation of how deadly our galaxy can be, filled as it is with exploding stars and stellar close encounters. Even where planets do exist, they may not be fit for complex life-forms.

Overview/Habitable Zone

- What does a planet need to support complex life-forms? Astronomers have generally focused on the stability of surface water—which is possible only within a certain range of distances from the planet's star, a region known as the circumstellar habitable zone. But in discovering extrasolar planets over the past five years or so, researchers have come to appreciate a broader set of conditions.
- Ideally, the star and its planetary retinue should orbit within a certain range of distances from the center of the galaxy. Too far, and the nebula from which the star emerged will lack the heavy elements out of which planets are made. Too close, and hazards such as orbital instabilities, cometary collisions and exploding stars will nip ecosystems in the bud. The sun's position is just right.
- All this suggests that complex life is rare in the galaxy.

Where's the Wherewithal?

THE BOUNDARIES of the galactic habitable zone are set by two requirements: the availability of material to build a habitable planet and adequate seclusion from cosmic threats. The story of how chemical elements came to be assembled into Earth is one told by modern cosmology, stellar astrophysics and planetary science. The big bang produced hydrogen and helium and little else. Over the next 10 billion years or so, stars cooked this raw mix into a rich stew of elements. Within the interstellar medium, the ratio of the number of metal atoms to the number of hydrogen atoms—that is, the “metallicity”—gradually increased to its present value.

These metals are the building blocks of Earth-like planets, and their abundance affects the size of the planets that can form. Size, in turn, determines whether a planet can retain an atmosphere and sustain geologic activity. Moreover, without enough metals, no giant planets can form at all, because they coalesce around a rocky core of a certain minimum size. Ob-

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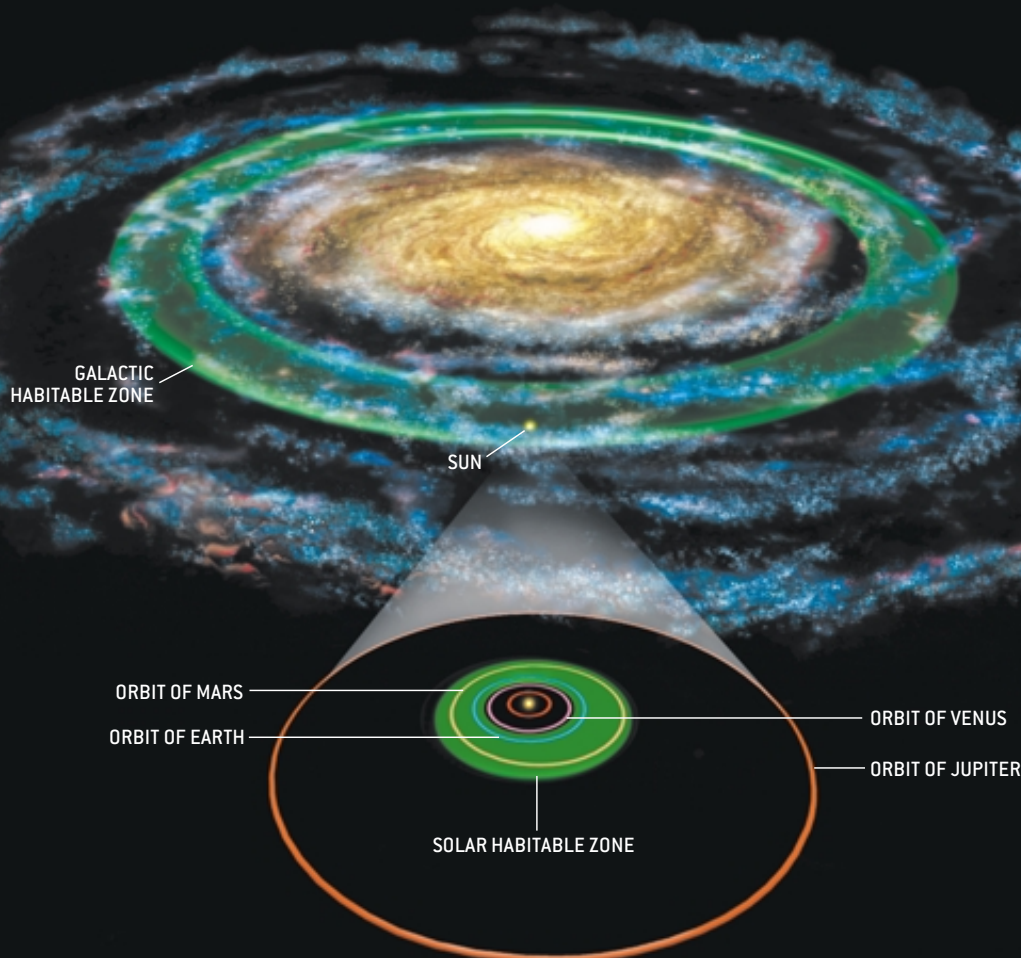
Observations of extrasolar planets are beginning to define the required metallicity for building giant planets. No such planet has been found around any star with a metallicity of less than 40 percent of the sun's. In a study reported last year, the Hubble Space Telescope failed to detect any planets in the globular cluster 47 Tucanae, whose stars have metallicities of 25 percent of the solar value [see "Searching for Shadows of Other Earths," by Laurance R. Doyle, Hans-Jörg Deeg and Timothy M. Brown; SCIENTIFIC AMERICAN, September 2000].

Conversely, too high a metallicity can also be a problem. Terrestrial planets will be larger and, because of their stronger gravity, richer in volatile compounds and poorer in topographic relief. That combination will make them more likely to be completely covered with water, to the detriment of life. On Earth, the mix of land and sea is important for atmospheric temperature control and other processes. High metallicity also increases the density of the protoplanetary disk and thereby induces the giant planets to shift position [see "Migrating Planets," by Renu Malhotra; SCIENTIFIC AMERICAN, September 1999].

A by-product of this orbital migration is that it will fling any smaller, Earth-like bodies out of the system altogether or shove them into the sun. As the elephants move around, the ants get crushed.

In a recent study, Charles H. Lineweaver of the University of New South Wales in Australia explored the dependence of planet formation and migration on metallicity. He assumed that the probability of forming a terrestrial planet is proportional to the metallicity of the parent star, because both the star and the planet arose from the same cloud of dust and gas. From the extrasolar planet statistics, he inferred that the probability of giant-planet migration rises steeply with increasing metal-

HABITABLE ZONE of the Milky Way (*green*) excludes the dangerous inner regions and the metal-poor outer regions of our galaxy. It is analogous to the habitable zone on the much smaller scale of our solar system (*inset*). Neither zone has sharp boundaries. The bulge is shown as yellow and the active star-forming regions in the spiral arms as blue and pink.



licity, with migration inevitable if the metallicity is 300 percent of the solar value. Although Lineweaver's calculations are tentative, they suggest that a metallicity near the sun's may be optimal for the production of Earth-mass planets in stable orbits.

Through Thick and Thin

ONLY PART OF THE MILKY WAY satisfies this requirement. Astronomers usually subdivide the Milky Way into four overlapping regions: halo, bulge, thick disk and thin disk. Stars in each region orbit the galactic center much as planets in our solar system orbit the sun. The halo and thick disk tend to contain older, metal-poor stars; it is unlikely that terrestrial planets as large as Earth have formed around them. Stars in the bulge have a wide range of metallicities, but cosmic radiation levels are higher there.

The thin disk is the sun's home. The metallicity of its gas declines with distance from the galactic center. At the sun's location, about 8.5 kiloparsecs (28,000 light-years) out, it is decreasing at 17 percent per kiloparsec. The logarithm of the metallicity (which astronomers give in units called "dex," the sun having a value of 0 dex, by definition) falls off linearly with distance, with a slope of -0.07 dex per kiloparsec. Observers measure the metallicity gradient using spectral features in various classes of stars and nebulae. The different indicators have converged onto the same answer only within the past three or four years, and galaxies similar to the Milky Way are now known to have similar disk metallicity gradients.

The gradient is an outcome of variations in the star-formation rate. Farther from the center of the galaxy there is proportionately less gas and therefore less star formation. Consequently, the outer reaches of the galaxy have built up less metal than the inner parts. In the galaxy as a whole, the star-formation rate peaked about eight billion to 10 billion years ago and has been declining ever since. Today the metallicity in the solar neighborhood is increasing by about 8 percent every billion years. As the gas supply dwindles, the metallicity will grow at an ever slower rate.

Taking into account the disk metallicity gradient and its evolution, we can place rough limits on the GHZ both in space and in time [see illustrations on page 66]. Stars forming today with a metallicity of between 60 and 200 percent of the sun's value generally reside between 4.5 and 11.5 kiloparsecs from the galactic center—a region that contains only about 20 percent of the stars in the galaxy. Moreover, the typical star in the solar neighborhood did not reach the 60 percent threshold until five billion to six billion years ago. The sun itself is about 40 percent richer in metal than other stars formed at the same time and location in the disk. This increased metal content may have given life on Earth a head start.

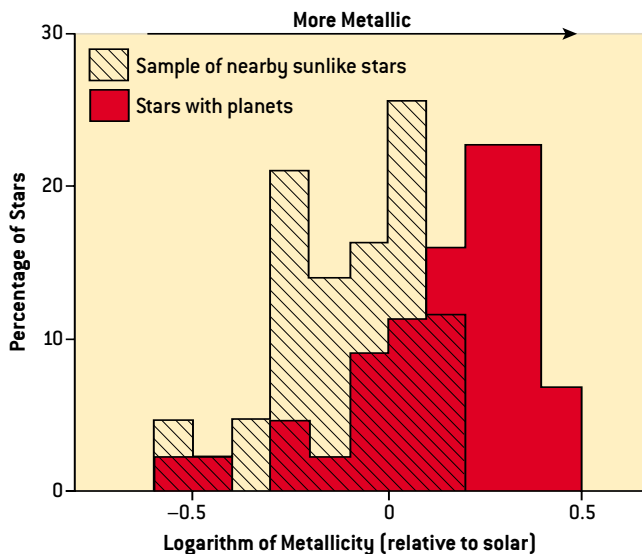
Iron Curtains

ONE POTENTIAL COUNTERARGUMENT is that the correlation of metallicity and detected planets is not the same as causation. Perhaps the causation goes in the opposite direction: instead of high stellar metallicity explaining the presence of giant planets, the presence of giant planets might explain the high stellar metallicity. This would happen if they tended to fall into the stars, enriching their metal content. Most astronomers now think that stars do gobble up planets and smaller bodies. But the outer convective layers of sunlike stars are so massive and so well mixed that they would need to devour an unreasonable amount of planetary material to fully account for the high metallicities seen among stars with planets.

Another rejoinder is that the correlation might be an observational bias. It is harder to spot planets around metal-poor stars; the leading planet search method relies on stellar spectral lines, which are weaker when a star has less metal. But the detection efficiency does not suffer appreciably until a star's metallicity drops below about 10 percent of the sun's value—which is well below the 40 percent threshold needed for giant planets. The observed correlation with planets is quite real.

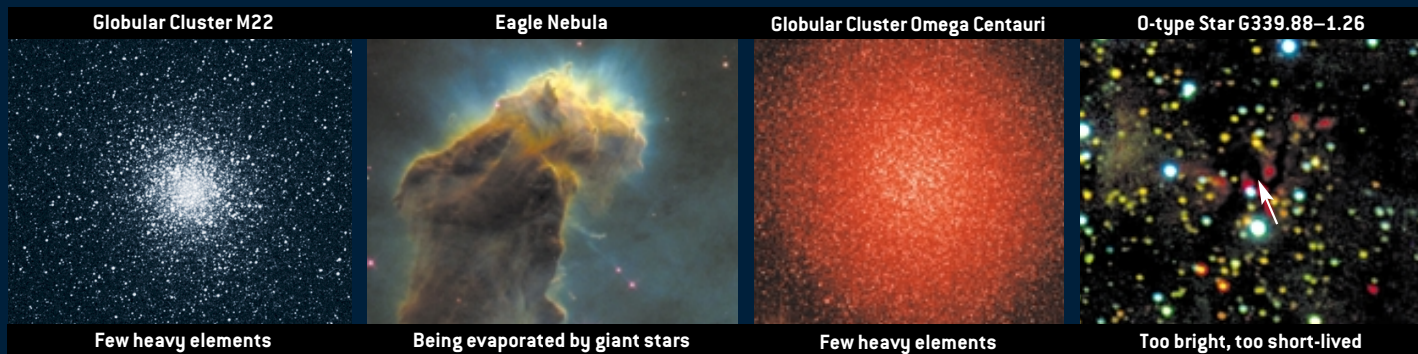
Metallicity is not the only compositional prerequisite for habitable planets; the relative abundances of different elements matter, too. The most abundant elements on Earth were produced primarily in supernova explosions, of which there are two basic types. Type I events, most of which result from the detonation of a white dwarf star, produce mainly iron, nickel and cobalt. Type II supernovae, which entail the implosion of a massive star, mostly synthesize oxygen, silicon, magnesium, calcium and titanium. Crucially, type II events are also the sole natural source of the very heaviest elements, such as thorium and uranium.

Because star formation in our galaxy is tapering off, the overall rate of supernova explosions is declining—as is the ratio of type II to type I events. Type II supernovae involve short-lived massive stars, so their rate closely tracks the star-formation rate. The rate of type I supernovae, on the other hand, depends on the



SURVEYS OF EXTRASOLAR PLANETS conducted by astronomers have revealed how important the supply of planet-building material is. As this histogram shows, the stars that are parents to giant planets (red area) tend to have a greater abundance of heavy elements ("metals") than the average nearby sunlike star does (black).

SARA CHEN; SOURCE: NUNO C. SANTOS/Geneva Observatory



Globular Cluster M22

Eagle Nebula

Globular Cluster Omega Centauri

O-type Star G339.88-1.26

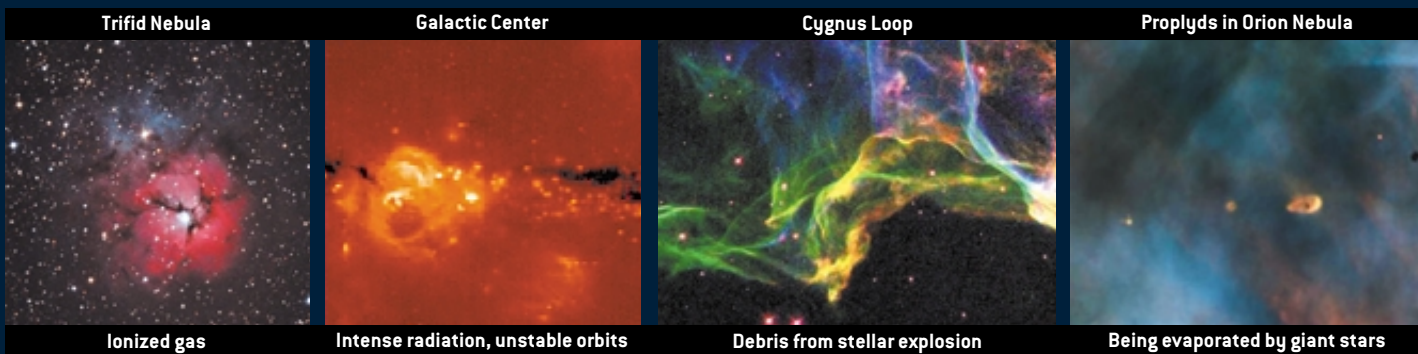
Few heavy elements

Being evaporated by giant stars

Few heavy elements

Too bright, too short-lived

WHAT IS BEAUTIFUL is often dangerous, in space as on Earth. Some of the most renowned sites in the galaxy are hostile to planets, let alone living things. The safest places in the galaxy tend to be the most boring ones.



Trifid Nebula

Galactic Center

Cygnus Loop

Proplyds in Orion Nebula

Ionized gas

Intense radiation, unstable orbits

Debris from stellar explosion

Being evaporated by giant stars

production of longer-lived intermediate-mass stars, so it responds more slowly to changes in the star-formation rate.

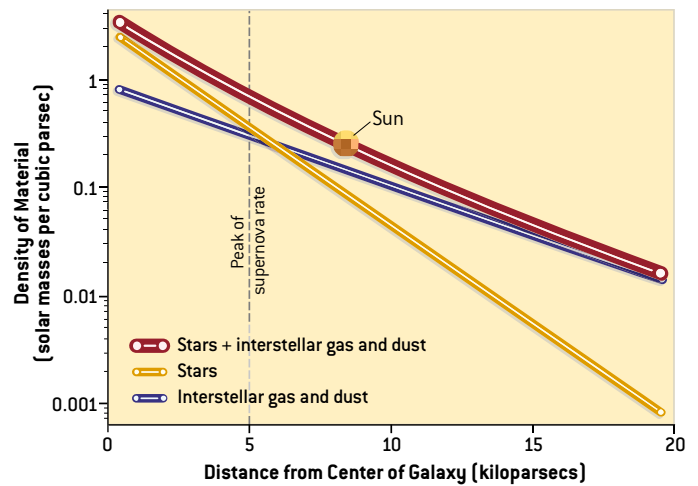
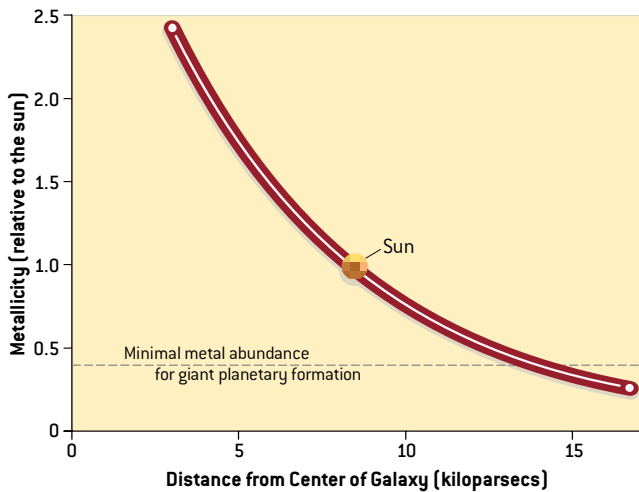
As a result of the shifting supernova ratio, new sunlike stars are richer in iron than those that formed five billion years ago. All else being equal, this implies that a terrestrial planet forming today will have a proportionately larger iron core than Earth does. It will also have, in 4.5 billion years, about 40 percent less heat from the decay of potassium, thorium and uranium. The heat generated by these radioactive isotopes is what drives plate tectonics, which plays an essential role in the geochemical cycle that regulates the amount of carbon dioxide in our atmosphere. Perhaps terrestrial planets forming today would be single-plate planets like Venus and Mars. The lack of plate tectonics on Venus contributes to its hellish conditions [see “Global Climate Change on Venus,” by Mark A. Bullock and David H. Grinspoon; *SCIENTIFIC AMERICAN*, March 1999]. But we do not yet understand all the ways a planet’s geology depends on its internal heat flow.

Danger, Danger

EVEN IF YOU MANAGE to get all the necessary atoms in the right place at the right time to build an Earth, you may not be justified in sticking a “habitable” label on it. A planet must also be kept reasonably safe from threats. These threats can be put into one of two categories: impacts by asteroids and comets, and blasts of radiation.

In our solar system the frequency of asteroid impacts depends on the details of Jupiter’s orbit and formation; the rest of the galaxy has no direct effect. The cometary threat, on the other hand, is quite sensitive to the galactic environment. Comets are thought to reside in two long-term reservoirs, the Kuiper belt (which starts just beyond Neptune) and the Oort cloud (which extends halfway to the nearest star). Other stars probably have similar reservoirs. Infrared observations of young nearby stars indicate that most are surrounded by excess dust, consistent with the presence of Kuiper-belt objects. More recently, detection of water vapor around the highly evolved luminous

THE AUTHORS *GUILLERMO GONZALEZ, DONALD BROWNLEE and PETER D. WARD* share an interest in the habitability of planets—both because they happen to live on one and because habitability is an intellectual challenge that draws on nearly every field of astrophysics and geophysics. The three are members of the astrobiology program at the University of Washington, which NASA recently awarded an astrobiology grant. Gonzalez, currently at Iowa State University, earned his doctorate at Washington studying the compositions of highly evolved stars in globular clusters. Brownlee specializes in the study of comet dust and meteorites and is the principal investigator for the Stardust mission, which plans to return comet dust samples to Earth in January 2006. Ward, a paleontologist, studies global mass extinctions.



star IRC+10216 has been interpreted as evidence of evaporating comets. Changes in the shapes of certain spectral lines in Beta Pictoris, a young star with a dust disk, could be caused by infalling comets.

Because Oort-cloud comets are only weakly bound to the sun, it doesn't take much to deflect them toward the inner planets. A tug from galactic tides, giant molecular clouds or passing stars can do the trick [see "The Oort Cloud," by Paul R. Weissman; *SCIENTIFIC AMERICAN*, September 1998]. The frequency of such perturbations depends on our position in the Milky Way. As one goes toward the galactic center, the density of stars increases, so there are more close encounters. Moreover, a planetary system forming out of a metal-rich cloud will probably contain more comets than one forming out of a cloud with less metal. Thus, planetary systems in the inner galaxy should suffer higher comet influxes than the solar system does. Although the outer Oort cloud in such a system will become depleted more rapidly, it will also be replenished more rapidly from the inner cometary reservoirs.

High-energy radiation, too, is a bigger problem in the inner regions of the galaxy. Up to a point, a planet's magnetic field can fend off most particle radiation and its ozone layer can screen out dangerous electromagnetic radiation. But sufficiently energetic radiation can ionize the atmosphere and generate nitrogen oxides in amounts capable of wiping out the ozone layer. Energetic radiation hitting the atmosphere can also let loose a deadly rain of secondary particles.

The nastiest radiation events are, in order of decreasing duration, active galactic nucleus outbursts, supernovae and gamma-ray bursts. The nucleus of the Milky Way is currently relatively inactive; the supermassive black hole at the heart of our galaxy appears to be dormant. But observations of other galaxies suggest that central black holes occasionally turn on when a star or cluster wanders too close and is pulled to its death. The result is a burst of high-energy electromagnetic and particle radiation. Most of the radiation is emitted in a jet along the rotation axis of the galaxy, but many of the charged particles will

LOCATION OF HABITABLE ZONE is determined by a balance between the supply of planet-building material and the prevalence of threats. The supply falls off with distance from the galactic center (*left*), while the density of stars—a proxy for perils such as stellar explosions and close encounters—also decreases with distance (*right*). An acceptable compromise is reached somewhere in the middle, although astronomers cannot yet pin down the precise location.

spiral along the galaxy's magnetic field lines and fill its volume. The worst place to be during such an outburst is in the bulge. Not only would the overall radiation levels be high, the stars there would tend to have highly inclined and elliptical orbits that could bring them close to the nucleus or jet.

Supernovae and gamma-ray bursts are also more threatening in the inner galaxy, simply because of the higher concentration of stars there. Observations of supernova remnants indicate that supernovae peak at about 60 percent of the sun's distance from the galactic center, where they are about 1.6 times more frequent than at our location. The threat from gamma-ray bursts remains uncertain; astronomers do not know what triggers these gargantuan explosions or how tightly they beam their radiation. We could just be lucky to have avoided such a death ray so far.

Radiation can also steal life from the crib. Sunlike stars are not born in isolation but rather are often surrounded by both low- and high-mass stars. The high levels of ultraviolet radiation emitted by the latter erode circumstellar disks around nearby stars, reducing their chances of forming giant planets. John Bally of the University of Colorado at Boulder and his colleagues have estimated that only about 10 percent of stars avoid this kind of harassment. This could explain why a mere 3 percent of nearby sunlike stars are found to have giant planets.

All these threats imply a fairly broad habitable zone with fuzzy boundaries. But if we include proximity to the corotation circle as another requirement, then the GHZ could be very narrow. The corotation circle is where the orbital period of a star equals the rotation period of the galaxy's spiral arm pattern.

When a star orbits at or very near the corotation circle, spiral arm crossings are less frequent. It will take longer to cross a spiral arm, but what is important is the relatively long period between crossings. Recent measurements of the dynamics of stars near the sun indicate that the sun orbits very near the corotation circle. The spiral arms may look pretty, but they are best appreciated from afar, because the intense star formation and giant molecular clouds within the arms multiply the risks to complex life-forms.

Paradox Lost

AT THIS STAGE of our research, we are still some way from filling in the details of the GHZ. Continuing studies of comets, galactic nuclei, supernovae, gamma-ray bursts and stellar dynamics will help pinpoint the threats to life. Even now, however, we have a broad picture of the GHZ. The inner regions of the galaxy suffer from orbital instabilities, radiation bursts and cometary perturbations. The outer regions are safer, but because of the lower metallicity, terrestrial planets are typically

meled by supernovae and an active nucleus. Only in the past five billion years or so could civilizations have safely arisen. The sun's relatively high metallicity probably gave us a head start. Therefore, the GHZ concept may provide at least a partial solution to the Fermi Paradox: complex life is so rare and isolated that we are effectively alone. To be sure, these implications apply only to complex life; simple organisms such as microbes could endure a much wider range of environments.

The broader universe looks even less inviting than our galaxy. About 80 percent of stars in the local universe reside in galaxies that are less luminous than the Milky Way. Because the average metallicity of a galaxy correlates with its luminosity, entire galaxies could be deficient in Earth-size planets. Another effect concerns the dynamics of stars in a galaxy. Like bees flying around a hive, stars in elliptical galaxies have randomized orbits and are therefore more likely to frequent their more dangerous central regions. In many ways, the Milky Way is unusually hospitable: a disk galaxy with orderly orbits, comparatively little dangerous activity and plenty of metals. It may

Any extraterrestrial civilization **SEEKING A NEW WORLD** would place our solar system on their home-shopping list.

smaller there. The GHZ appears to be an annulus in the disk at roughly the sun's location [see illustration on page 63]. The GHZ is a probabilistic concept: not every planet inside the zone is habitable (and not every planet outside is sterile). But the probability is much greater inside. The GHZ has been slowly creeping outward, as interstellar gas reaches solar metallicity.

The GHZ concept has important implications for searches for extraterrestrial intelligence. It can, for example, identify the most probable places for complex life to form, so that researchers can direct their searches accordingly. We can already say with some confidence that globular clusters, the outer disk and the galactic center make poor targets.

The GHZ concept also has implications for the debate swirling around the Fermi Paradox: If our galaxy is teeming with other civilizations, we should see some evidence of their existence; we do not, so perhaps we are alone [see "Where Are They?" by Ian Crawford; *SCIENTIFIC AMERICAN*, July 2000]. One of the arguments proposed to avoid that conclusion is that ETs may have no motivation to leave their home world and scatter signs of their presence through space. But if our ideas about the GHZ are correct, we live within an especially comfortable region of the Milky Way. Any civilization seeking a new world would, no doubt, place our solar system on their home-shopping list. The GHZ theory also weakens the argument that the galaxy is so big that interstellar explorers or colonizers have passed us by. The GHZ may be large, but it is just a part of the entire galaxy, and any galactic travelers would tend to roam around the annulus rather than haphazardly through the galaxy.

Furthermore, the GHZ concept constrains habitability not just in space but also in time. The Milky Way used to be pum-

not remain so for long. The Andromeda galaxy is predicted to have a close encounter with the Milky Way in about three billion years. That event will dislodge most stars in the disk from their regular orbits. It may also pour fresh fuel onto the Milky Way's central black hole and cause it to flare up, with possibly unhappy consequences for the inhabitants of Earth.

Douglas Adams, that great expositor of simple truths, famously summed up what he took to be the product of the past few centuries of progress in astronomy: "Far out in the uncharted backwaters of the unfashionable end of the western spiral arm of the Galaxy lies a small unregarded yellow sun." But as is often the case, fashionable is not the same as comfortable. We live in prime real estate. SA

MORE TO EXPLORE

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