

single light element: "Of all the likely contributors (other than iron), no one element is likely to be more abundant than all the others put together. What you have is a liquid metal alloy of many components, one of which is hydrogen."

RAY LADBURY

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SOHO Observations Implicate 'Magnetic Carpet' as Source of Coronal Heating in Quiet Sun

If you image the Sun in x rays or the extreme ultraviolet, you'll see its corona, a halo of million-degree gas whose spectacular structures, known as active regions, are associated with photospheric sunspots. Between the active regions, and covering most of the solar surface when sunspots are absent, is the so-called quiet corona, which glows less brightly and varies more modestly. An accurate explanation of exactly how the corona is heated has long eluded researchers, and, until now, they have found it relatively easier to make progress in the case of the active regions than the quiet Sun.

In the 1970s, NASA's Skylab experiment confirmed that the active regions are directly associated with huge loops of magnetic field, which, after being generated in the solar interior by the dynamo effect, burst out of the surface like intestinal hernias. Though not fully worked out, the theory of magnetic reconnection links the magnetic flux tubes to the heating of the hot coronal gas. As turbulence jostles the flux tubes, they can abruptly snap into configurations of lower energy by "reconnecting" to nearby tubes of opposite polarity. The sudden release of magnetic tension accelerates and heats the plasma entrained in the tubes.

To explain the observed distribution of magnetic fields over the solar surface, the late Robert Leighton of Caltech proposed that flux disperses from large active regions through a random walk driven by the (mostly) horizontal movement of convective cells known as supergranules. Differential surface rotation also helps to spread the flux. Subsequently, models were refined to include poleward, meridional flow, but the basic idea remained that the magnetic field in the quiet Sun and the corresponding coronal emission were by-products of the active regions.

Things quick and bright

That perception of the quiet Sun prevailed because little evidence of magnetic activity was gathered over the typical hour-long timescales during which the photosphere was observed from Earth. Bright, evanescent regions could be seen in the quiet Sun,

The mystery: How is energy transferred from the Sun's 5800 K photosphere to heat the star's 3 million K corona? One likely mechanism, at least for the quiet Sun, involves short-lived loops of magnetic field that sprout on the solar surface—and resemble some kind of energetic celestial shag carpet.

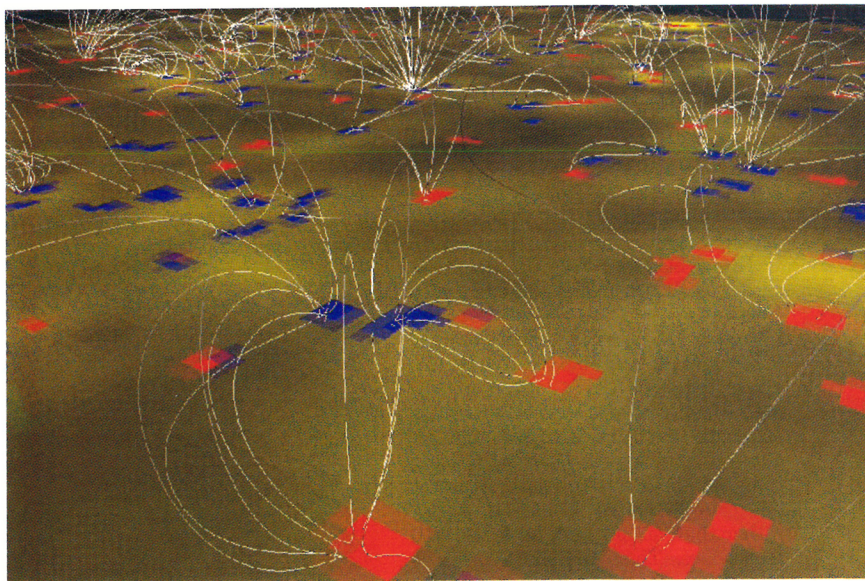
but those researchers who studied them—principally Karen Harvey of Solar Physics Research Corp in Tucson, Arizona—were hampered by the constraints of ground-based observing.

That situation changed with the launching in 1995 of SOHO, a joint European Space Agency–NASA mission devoted to studying the Sun's interior, exterior and wind. SOHO,

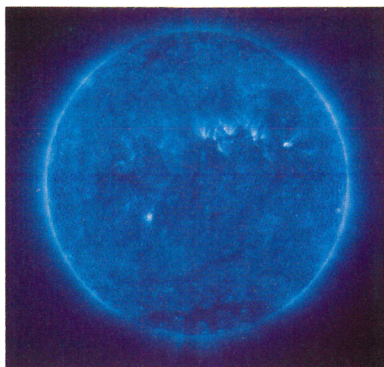
which stands for Solar and Heliospheric Observatory, is kept in a tight "halo" orbit around the L1 Lagrangian point between the Sun and Earth, the place where the gravitational pulls of the two bodies are equal and opposite. From that vantage point, SOHO can observe coronal structures with unprecedented spatial resolution 24 hours a day.

Inspirational carpets

Using SOHO's Michelson Doppler Imager (MDI), Alan Title and his colleagues at the Stanford–Lockheed Institute for Space Research in Palo Alto, California, constructed magnetograms of the quiet Sun every minute or so. The magnetograms, which use polarized light to find magnetic concentrations, revealed that small magnetic



A SNAPSHOT OF THE MAGNETIC CARPET is shown here in this composite image. Yellow indicates the extreme-ultraviolet flux as measured by the Extreme Ultraviolet Imaging Telescope. The paler the yellow, the brighter the flux. Overlaid on the EIT image are red and blue patches—about 10 000 km apart—that correspond to where the Michelson Doppler Imager detected magnetic fields of opposing polarities (blue for into the surface, red for out of the surface). Also shown are the field lines in the solar corona as modeled using a potential field based on the observed magnetic map. The potential field model is an oversimplification, but gives a good impression of the very complicated field geometry in the solar corona. (Courtesy of Karel Schrijver, Stanford–Lockheed Institute for Space Research.)



BY OBSERVING EMISSION LINES from highly ionized iron IX and X, SOHO's Extreme Ultraviolet Imaging Telescope reveals how the corona's 10^6 K gas is shaped by the Sun's magnetic field. (Courtesy of the SOHO-EIT consortium.)

loops are perpetually sprouting on the solar surface and then disappearing. To Title, the tangle of small loops looked like a carpet.

The rate at which the carpet's magnetic loops regenerate was the biggest surprise. Totting up all the disappearances, Title found that the entire magnetic carpet replenishes itself every 40 hours.¹ Omitted from Leighton's diffusion model, the rapid replenishment requires, according to Title, a "fundamental change in the way we picture the formation of flux." SOHO team member Joe Gurman from NASA's Goddard Space Flight Center nearly fell out of his chair when he first heard about the rapid replenishment. "It's one of those things that changes your view, catastrophically, of what's going on," he says.

Direct evidence that the magnetic carpet really can heat the corona comes from two other SOHO instruments, the Coronal Diagnostic Spectrometer (CDS) and the Extreme Ultraviolet Imaging Telescope (EIT). Both instruments have recorded local brightenings of hot gas that coincide with disappearances of the carpet's loops, indicating that just about all the loops reconnect and cancel, thereby releasing energy, rather than simply sink back beneath the surface. The figure on the previous page shows that the magnetic loops occur on the surface in the same places as the local brightenings measured by EIT.

The statistical correlation of EIT and CDS brightenings with MDI loops is still under way, but, says Richard Harrison, who leads the CDS instrument team from the UK's Rutherford Appleton Laboratory, "First results are very encouraging. . . . I think it is pretty clear that the rela-

tionship is close."

One consequence of the magnetic carpet is that it dramatically boosts the amount of magnetic energy available to heat the corona. Over the coarse 100 000 km grid of Leighton's model, many opposite-polarity concentrations in the mixed-polarity regions cancel when you calculate averages. As much as 90% of the flux could be missed. And if you observe the carpet's rapid replenishment of flux too slowly, you'll drastically underestimate how much new flux contributes to the total. Since energy goes as the square of the field, the discrepancy can be enormous, and much more energy is available to heat the corona than previously realized—although, cautions Title, "It'll be a few years before we can tell you exactly what the numbers are."

Spirits from the vasty deep

Pinning down the origin of the carpet is tricky. What's clear, however, is that it's related somehow to the Sun's dynamo. Karen Harvey found that the loops of the carpet are closest together at the same latitudes where the larger active regions emerge. And, in a given solar cycle, the loops' fields display a weak preference for the same alignment as those of the active regions.

Consistent with these observations are two basic ideas: Either the carpet is formed in the same way as the larger, dynamo-generated field; or it's produced independently but influenced by the dynamo.

If carpet and dynamo are indeed cut from the same cloth, then the question shifts to explaining how it is that both

large and small pieces are produced. Large concentrations of dynamo-generated flux arise from deep in the interior of the Sun and float upward by magnetic buoyancy to emerge as active regions. It's conceivable that the carpet corresponds to small bits of flux that break off during their ascent. Another possibility, explains Title's colleague Karel Schrijver, is that large and small flux concentrations form at the same depth. Some support for this idea comes from observations made by Harvey, who has found that the rates at which large and small concentrations emerge, while correlated and in phase with one another, differ by more than a factor of four in amplitude.

Alternatively, turbulent motion in the upper convection zone could generate the carpet—a mechanism originally proposed in 1993 by Bernard Gurney of the National Solar Observatory in Tucson.

Oranges are not the only fruit

To astronomers, the Sun is not the most interesting star, merely the closest. What does the Sun's magnetic carpet imply for other stars? According to Tom Ayres (University of Colorado at Boulder), one of the main implications is that stars—red giants in particular—can have low levels of magnetic activity without the need for a dynamo churning away in the stellar interior.

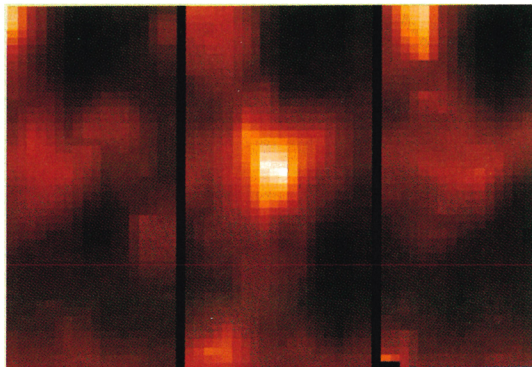
Red giant stars were long thought to be magnetically inactive. Not only do they lack the x-ray emission that characterizes active regions, but they're so bloated that they spin too slowly for the dynamo mechanism to

Goodness Gracious, Small Balls of Fire!

It was only last year that "blinkers," the latest addition to the rich lexicon of solar phenomenology, were discovered by SOHO's Coronal Diagnostic Spectrometer (CDS). Lasting a few minutes, they appear as Earth-sized explosions—3000 or so pop off at the same time on the solar surface.

The three accompanying panels show the same area on the Sun, but not at the same time. The middle picture, which catches a blinker *in flagrante*, was taken 24 minutes after the left picture and 10 minutes before the right picture. As measured by CDS, the temperature of the fireball is 250 000 K, which places the event in the transition region just underneath the corona.

"Blinkers and the magnetic carpet are intimately linked," says Richard Harrison. Indeed, using Michelson Doppler Imager data, Ted Tarbell (Stanford-Lockheed Institute for Space Research) has found that blinkers and carpet loop cancellations occur in the same places, many simultaneously. (Courtesy of Richard Harrison, Rutherford Appleton Laboratory.)



generate a substantial field.

This neat consistency of theory and observation changed when observations with the Goddard High Resolution Imaging Spectrometer (which was removed in 1997 from the Hubble Space Telescope) showed that red giants do indeed have hot patches of activity. Moreover, the emission lines that trace the activity are stamped

with the effects of absorption in cooler material. If reconnecting magnetic loops are responsible for the activity, then they lie within the red giant's cool atmospheric envelope and close to the stellar photosphere—like the loops of the Sun's magnetic carpet.

Though acoustic waves could also be responsible, Ayres speculates that the magnetic carpet is generated by

Gurney's turbulent dynamo in the upper convection zone. "And that kind of mechanism," suggests Ayres, "could work on all stars."

CHARLES DAY

Reference

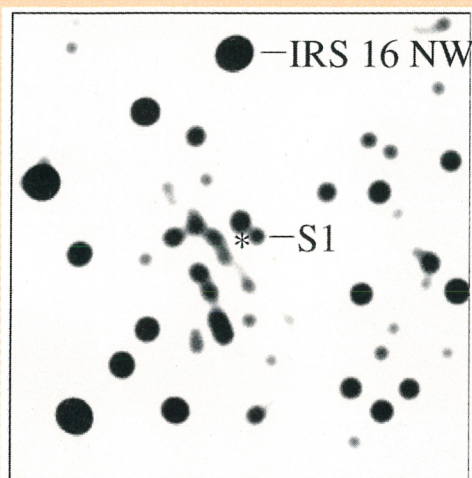
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Stellar Motion Very Near the Milky Way's Central Black Hole

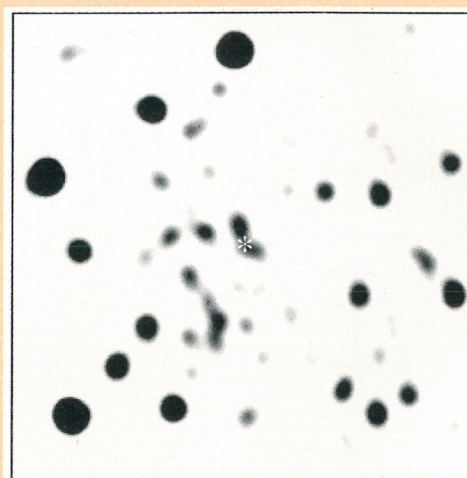
The extraordinary pair of images at right are near-infrared exposures, taken two years apart, of stars in the central 3×3 -arcsecond field of our Galaxy. Andreas Eckart and colleagues at the Max Planck Institute for Extraterrestrial Physics in Garching, near Munich, have been monitoring the proper and Doppler motions of these stars since 1992 with spectacularly high-resolution infrared speckle photography and spectroscopy, using European Southern Observatory telescopes, in Chile, optimized for infrared observation. At visible wavelengths, the central precincts of the Galaxy are completely hidden by dust.

Eckart and company describe their observations as "the first conclusive evidence for a massive black hole in the center of the Milky Way."¹ The Galactic center, 26 100 light-years from us, is associated with the very compact radio source Sagittarius A*, marked by the asterisks in the images. At that distance, 1 arcsecond = 46 light-days.

In the color closeup of the innermost arcsecond (with Sgr A* marked by the red cross), the measured proper velocities (that is, in the plane normal to the line of sight) are indicated by the lengths and directions of the blue arrows. Together with the Doppler radial velocities, they exhibit a Keplerian decrease with distance from Sgr A*. There is no obvious preferred orbital plane. The fastest moving star, marked S1, changed position quite noticeably from 1994 to 1996. Less than a light-week from Sgr A*, it has a velocity in excess of 1500 km/s. That's about four times the velocity of the star IRS 16 NW, which is more than two light-months from Sgr A*.



April 1994



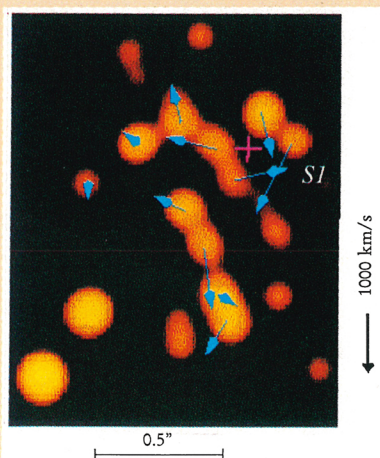
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From the measured Keplerian stellar velocities and distances, Eckart and company conclude that Sgr A* marks a compact object of 2.6 million solar masses at the center of the Milky Way. The small distances to the innermost orbiting stars tell us that this supermassive concentration is far denser than any known star cluster. And if it were a uniquely dense star cluster, it would be unstable on a time scale much shorter than the age of the Galaxy. Furthermore, the stringent upper limit on any proper motion by the

radio source Sgr A* implies that at least 10^5 solar masses are enclosed within 1 astronomical unit (the Earth's orbital radius, 8 light-minutes). "So the only plausible explanation" Eckart told us, "is a supermassive black hole."

Of course, this is not the first evidence for a great concentration of mass near the center of a galaxy. But this first observation of stellar motion within light-days of the center of any galaxy appears to exclude anything but a black hole in the case of the Milky Way. Aside from being much closer in than the gases that have been observed moving rapidly near galactic centers, stars are better gravitational test particles, because gases can be diverted by pressure gradients and magnetic fields. The Garching group's observations have now been confirmed by a University of California, Los Angeles, group doing infrared imaging with the 10-meter Keck telescope in Hawaii.²

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