Desperately Seeking Kepler

Cool stars — of which the sun is one — bring together solar and stellar astronomers in a fast-growing new field of study

By DIETRICK E. THOMSEN

It seems to have started with starspots. Astronomers have been studying sunspots since about 1600, and have always supposed that other stars have similar features. About three years ago astronomers figured out how to draw pictures of starspots (SN: 7/17/82, p. 36). Other new observational possibilities arose. Suddenly, details of surface and internal dynamics of stars that were impossible to study years ago have become available. As a result, cool stars – those with surface temperatures of less than about 10,000 kelvins – are a hot topic.

Douglas S. Hall of Vanderbilt University's Dyer Observatory in Nashville, Tenn., compares this situation to that of planetary astronomy at the end of the 16th century: "We have Tycho Brahe's observations; we need a Kepler" to analyze them and derive general principles from them. Cool stars drew about 150 specialists to the Fourth Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, which was held recently in Santa Fe, N.M., but Johannes Kepler did not appear.

The field is firmly anchored in 400 years of observations of the sun, which is, as Sallie L. Baliunas of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Mass., called it, "the star whose activity cycle we know most about." The most obvious solar activity is sunspots. They are easy to see on the projections of the sun that solar telescopes throw on screens – nobody ever *looks through* a solar telescope – and people have been counting them since Galileo's day.

The most basic piece of information gained from this activity is that the number of sunspots varies periodically. As Baliunas points out, the periodicities are more complicated than people referring to the "11-year cycle" might assume. There is a distribution of periods between eight and 15 years, she says. Then there is evidence for a cycle upwards of 100 years superimposed on the shorter cycle. In addition to everything else, epochs of low activity seem to occur every fourth millennium.

Astronomers now look for similar cycles on other stars. The way to determine the prevalence of starspots is to follow changes in the star's brightness from time to time.

The periodicities can vary widely. Baliunas cites, for example, the star Lambda Andromedae, which in the records "can be followed over years, nightly or nearly nightly. The star brightens to spot minimum. It looks like a six-year cycle." But that cycle is not yet entirely clear. There are some very long periods (BY Draconis seems to have a 60-year period), and there are some shorter than the sun's.

Over the gamut of stars included in this study, which range over spectral classes F through M, Baliunas distinguishes three broad classes of variation: "fairly flat, smooth variation like the solar cycle, and very erratic." She notes, "It is still a project in its infancy. Periods longer than nine years haven't had several cycles measured." Olin Wilson of the Mt. Wilson and Las Campanas Observatories in Pasadena, Calif., was cited at the meeting for 18 years of observations that have brought things that far. The future will require precise and dedicated measurements in the long term, Baliunas says.

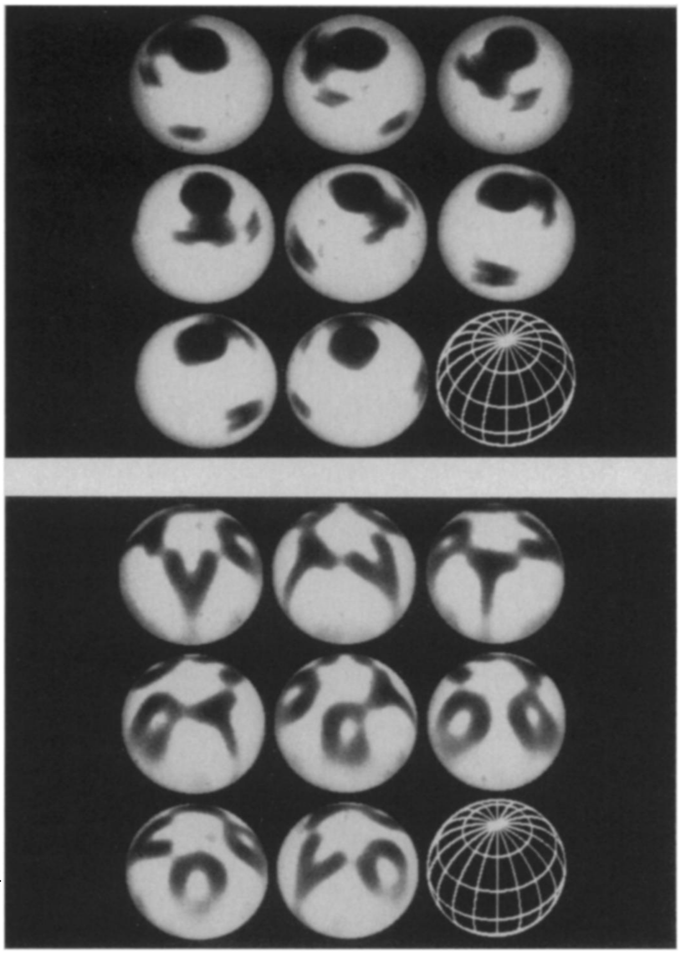
It could be quite long. David Gibson of New Mexico Tech in Socorro, speaking of solar magnetic activity, says, "If people had not observed the sun in the early 1600s we would not know of the Maunder minimum," a long period of extremely low solar activity. To an astronomer who expressed the prospect of lifelong activity studying cool stars, Gibson responded: "You and your children and your grandchildren."

Sunspots are associated with solar magnetic activity. Likewise, astronomers want to associate starspots with stellar magnetic behavior. Cornelis Zwaan of the Sonnenborgh Observatory in Utrecht, The Netherlands, considers the parameters that determine stellar magnetic activity, asking: "What are the best indicators to use?" The portion of a star's surface that is covered with spots at any time can be estimated from the star's brightness: The dimmer the star, the greater the spot coverage. Zwaan studies these variations in detail, particularly the changes in color contributed by changing intensity of the emissions of different elements that may lie at different levels in the star's outer layers. He compares the visible light and its color changes, which he attributes to the star's chromosphere or to the transition layer between the chromosphere and the corona, with the soft X-rays, which come from the corona.

Zwaan finds a complicated relation between a star's color changes and its rotation rate. He describes a "basal chromospheric flux," which he attributes to "maybe acoustic heating," and which he subtracts from the total flux. The difference, which contains the variations of brightness and color, he attributes to magnetic heating. "The really exciting stuff comes from the strong magnetic part of the chromosphere." And, he continues, "We have to find out for the sun how radiation fluxes relate to active periods."

Lee Hartmann of the Harvard-Smithsonian Center for Astrophysics responds, "For the sun much light has nothing to do with the chromosphere. Most light is from the photosphere [which underlies the chromosphere]. It's not surprising you have to subtract something for a correlation to activity. How much to subtract? There is no clear answer."

Another critic alleges that "we have not seen nonmagnetic heating even in the sun. To understand magnetic phenomena you have to measure the magnetic field." This is not easy to do, although radio observations can help, and as Gibson points out, radio observations are the only way to find out the sense — that is, the polarization — of the magnetic field.


Lick Obs./UC Santa Cruz

Data taken from the spectra of stars can be used to determine the existence and locations of starspots. The computer can then draw the spots on a representation of the star. Of the two examples here, one is an actual star, HR 1099 (top), and the other is a hypothetical exercise, put up by the developers of the method, to answer critics who say the method gives ambiguous results. The last name of astronomer Steven Vogt was written on a pretend star (see front cover). The spectrum that configuration would give was calculated and put through the program. The result, unambiguous enough according to Vogt and associates, appears here (bottom).

Vibration is another global activity of the sun. In recent years astronomers have found evidence for a whole spectrum of solar vibrations at a variety of frequencies. Assuming that such vibrations also happen on other stars, J. Christiansen-Dalsgaard of the Institute for Astronomy in Aarhus, Denmark, calls the subject "asteroseismology," a word he recommends for the next edition of the *Oxford English Dictionary*, and which, he says, was coined with the advice of a professor of classics who is expert on the Greek derivations of scientific terminology.

Asteroseismology can tell a great deal about the sun's interior. Each of the waves goes from the surface to some reflection point in the interior and back to the surface. Each different frequency reflects at a different point, so the whole spectrum gives information about different levels in the interior.

At the moment astronomers know a good deal about the sun and almost nothing about other stars. On what kind of stars would it be fruitful to look for such vibrational activity? Christiansen-Dalsgaard suggests Delta Scuti, ZZ Ceti and similar stars, the class known as Ap stars; the sun, of course; and solarlike stars in general. There's a trade-off, he says, between knowing the sun in enormous detail and knowing many stars in very little detail.

One of the things about which the sun's vibrations give information is the rate of rotation at various depths in the sun, and whether it varies from the rate at the surface. The evidence so far reveals a puzzling behavior, says Christiansen-Dalsgaard. Astrophysicists would have expected the surface to go faster than the interior. But the convection zone, the region below the surface that convects heat generated deep in the interior to the surface, rotates at the surface rate. Below the bottom of the convection zone the rotation rate declines a little and then rises a little. There's no explanation why.

Another piece of information from the vibrations is the speed of sound at various levels. The sound speed is related to various characteristics of motions taking place at the given location. In the convection zone, this information is particularly important, because the convection zone is the major theater of the actions that theorists see as giving rise to the sun's magnetic activity.

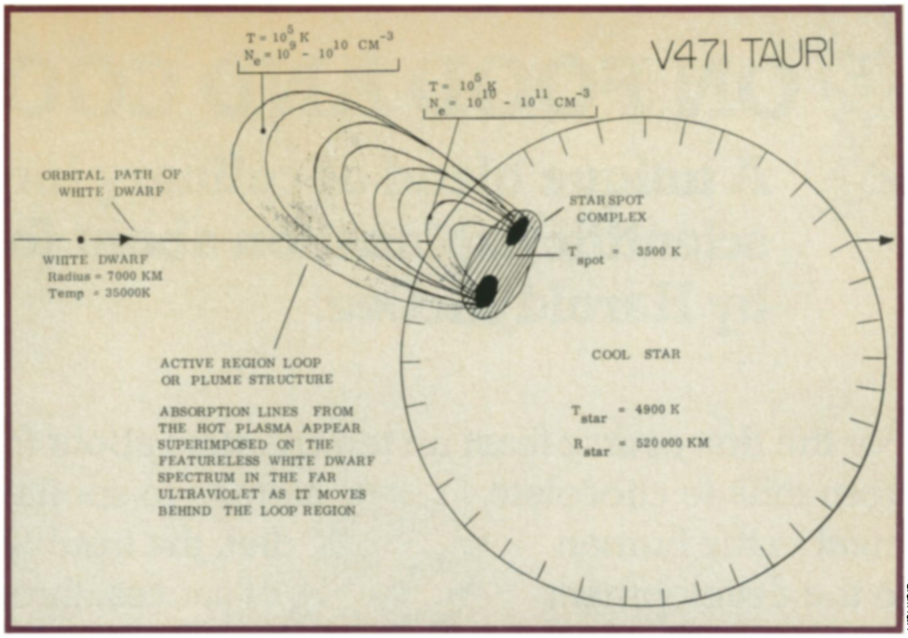
There are two dynamo theories of what goes on in the convection zone, says Peter A. Gilman of the High Altitude Observatory/National Center for Atmospheric Research in Boulder, Colo., and they both deal with virtually the same physics. They combine convective rolls rising from the bottom of the convection layer to the top and then descending again with two differential rotation effects: *on the surface* the equatorial regions go faster than the polar regions; *going to the interior* the rotation rate decreases. Combining these motions with the convective rolls — which take place in a plasma, an electrically conducting fluid — will make dynamos that generate magnetic fields. But there's a paradox here: In the theory the fields migrate toward the poles, the wrong direction for the sun.

Either the differential rotation theory or the dynamo theory is wrong, says Gilman. An attractive way out is to assume that the dynamics of the dynamo don't involve the whole of the convection zone but only a thin layer on the bottom of it, something like 10 kilometers thick. Such a theory could solve many of the dynamical problems by decoupling the differential rotations of the surface and the convection zone from the dynamo. To see whether the thin-zone model really works will require a knowledge of the detailed structure of the magnetic field in depth, says Gilman, and he calls that "a tall order."

Sunspots are connected with local manifestations of that field, and as astronomers have studied them over the centuries they have revealed much about the detailed structure and behavior of the sun. Starspots can do likewise, even though astronomers cannot get pictures of a star's disk with its spots from a telescope.

"Starspots are among the most remarkable phenomena," says Marcello Rodono of the University of Catania in Italy. They give evidence for small-scale structure in stars. From the observations of starspot-induced fluctuations in star brightness, astronomers can deduce temperatures of spots, the percentage of the star surface covered by spots and the distance of spots from the line of sight. Rodono says they try to make a model of a star with a feature on it, but there are too many ambiguities. The feature may be located elsewhere, symmetric to the place the astronomer has chosen to put it. "Uniqueness is just a dream," Rodono says.

However, certain pioneers in the business of visualizing starspots argue for a kind of definiteness. A few years ago Stephen Vogt and Donald Penrod of the University of California at Santa Cruz (UCSC) developed a way of constructing a drawing of spots on the surface of a star from the detailed data of the brightness of particular resonant emissions in its spectrum (SN: 7/17/82, p. 36). Artie Hatzes of UCSC, who now works with Vogt and Penrod, argued for a method of resolving the ambiguities in this procedure. They call it maximum entropy, and Hatzes says it is based on Occam's razor, the famous maxim that in any situation nature will choose the least complicated of possible procedures or explanations. Hatzes did not convince everybody at the workshop, however. Steven Shore of New Mexico Tech responded that "you can slit your wrists on Occam's razor."



Eclipses of binary star systems can be used to determine minute details of their surfaces and atmospheres. Here, in the system V471 Tauri, the existence of huge coronal loops in the atmosphere of the large cool star is deduced from the spectrum of the white dwarf as it passes behind the loops.

Rodono listed some of the data about starspots — unique or not — that can be "observed" in the photometric data about stars. The radii of starspots range from 15° to 40° (on the star surface). They cover between 2 percent and 10 percent of the star's surface. Their temperatures range from 2,600 kelvins to 4,100 kelvins, and they are cooler than the overall temperature of the surface, ranging from 70 percent to 85 percent of the overall temperature. Information on differences in surface rotation rate from pole to equator can also be gained.

Edward Guinan of Villanova (Pa.) University reports that atmospheric features of stars as well as surface features can be determined from photometric, spectroscopic and X-ray observations of starspots by taking advantage of the eclipses that occur in binary systems. These features include plages, coronal loops and X-ray hotspots in the corona. The strength of localized magnetic fields can also be determined from such spectroscopic details.

Guinan cites one spectacular example, the binary star V471 Tauri, sometimes known as the "gem of the Hyades." This system consists of a star of spectral class K and a white dwarf. An eclipse lasts 49 minutes; the binary orbital period is 12 hours 30 minutes. The K star has spots, and its spots can be cut off by the eclipse. (The white dwarf does not cover much.) One such spot has a temperature of 3,100 kelvins and is 100,000 kilometers across. At a point in the eclipse when light from the white dwarf is coming through the atmosphere of the K star, something like coronal loops can be seen. The loops extend about 400,000 kilometers from the K star's surface, and have a temperature of 100,000 kelvins at 100,000 kilometers from the surface.

Features like these are also seen on the sun. We know a good deal about the magnetic structure of the sun's atmosphere, Eugene N. Parker of the University of Chicago points out, but things may be different on other stars. "There may be things [there that are] missing from our repertoire because we are dependent on the sun." And the sun's situation is complex and by no means completely known in detail.

Parker seconds what Gilman says about the difficulties with dynamo theories of how the magnetic field is generated in the convection zone. He goes on to point out that when that field comes through the surface, it is characterized by a lot of fibrils. How these fibrils relate to each other, to active areas, spots and plages, how they stretch out into coronal loops, and whether they break off and send pieces of magnetic flux off into the universe to infinity are all questions not settled in detail.

The corona of the sun is a good deal hotter than its surface. In the sun's corona, says James Ionson of the NASA Goddard Space Flight Center in Greenbelt, Md., there are both "cool" loops of about 300,000 kelvins (seen in the extreme ultraviolet) and X-ray loops as hot as 1 million kelvins. A combination of electromagnetic and dynamic elements is responsible for this extreme heating — the sun's surface temperature is about 6,000 kelvins. One can assume that the same sort of heating mechanism is active in the coronas of stars of all varieties of spectral classes. It will take a collaboration of solar, stellar and plasma physicists to resolve all the outstanding problems in elucidating details of these mechanisms.

Finally, stars relate to their surroundings not only by emitting light and X-rays but also by emitting some of their material, in the form of stellar winds. Stephen A. Drake of SASC Technologies in Lanham, Md., gives as an example the mass loss rate of Betelgeuse, which has varied from some hundreds of thousands to 10 million times the sun's mass per year. Not many such rates have been measured by observation, and theoretical attempts to provide formulas for calculating them have come out wrong for the sun. Many such models start from one kind of star and extrapolate to others. "Beware of scaling laws," says Drake. "Do not extrapolate off the deep end."

Kepler hasn't yet arrived. Until he does, and for a long time after, cool stars are likely to remain a topic for dedicated, painstaking, cyclic and synoptic observations that could easily fill the lifetimes of astronomers. They may also fill the lifetimes of robots. Some astronomers, particularly Hall and Russell M. Genet of the Fairborn Observatory in Mesa, Ariz., are working on automated photometric telescopes for some of this work.

The long-term observation is not likely to be too expensive. In a discussion of ways and means, one commentator said he was pleased that "nobody has used the words 'space telescope.' A million dollars will buy one and one-half days of the space telescope's time, but $1 million buys a lot of cyclic and synoptic observations of stars." The work, he says, is "important and cheap." □