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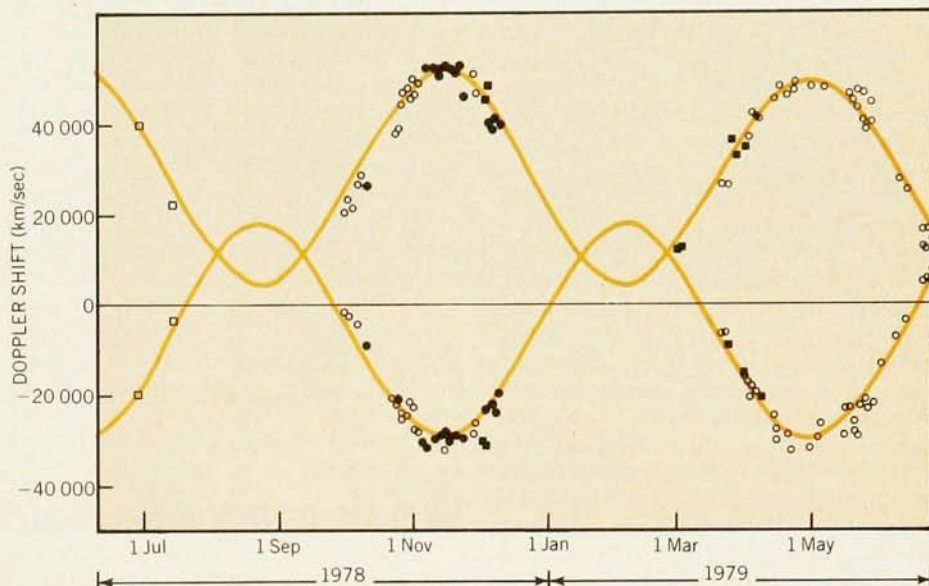
Puzzle of SS433: both a blue shift and a red shift

Recent observations confirm that a fourteenth-magnitude "peculiar" star in our galaxy is a bizarre object indeed, the like of which has not been seen before. Its spectrum exhibits hydrogen (Balmer) and helium emission lines with red and blue shifts indicating velocities up to 50 000 km/sec ($0.17c$), and these shifts vary roughly sinusoidally with a period of 164 days. The shifting lines are themselves comparatively narrow. The spectrum also contains unshifted hydrogen and helium lines.

The earlier results had suggested several interpretations, but the most recent results, some of them not yet published, appear to rule out most of them. The observations most strongly favor a kinematic model for the emission: Two particle beams emitted by a rotating or precessing object give rise to the shifting lines; the velocity of the emitting beams is $0.27c$, and the line shifts one sees arise from the Doppler effect due to the periodically varying velocity components along the line of sight. But, while the kinematics of the bizarre spectrum appear to be well established, there is as yet no clear idea as to the physical mechanisms that underlie the observed behavior.

The object was first noted in the 1960's and is listed in a catalog of peculiar stars compiled in 1977 by Charles Stephenson and Nick Sanduleak (Case Western Reserve University), where it is number 433. Subsequent observations recorded variable radio and x-ray emissions from the object. There is also a radio-emitting region, assumed to be a supernova remnant, whose brightest region is about 10-arc-min to the north; recent, as yet unpublished observations show that the remnant surrounds SS433, but it is not clear that there is any association between the two.

Earlier this year¹ Bruce Margon, Holland Ford, Jonathan Katz, Karen Kwitter and Roger Ulrich (all at UCLA), and Remington Stone and Arnold Klemola (at Lick Observatory) reported their first observations of SS433. These were a large number of high-resolution spectra obtained at Lick Observatory, together with a few from Palomar and Mount Wilson. In addition to intense hydrogen and ionized-helium lines and a strongly reddened continuum background, Margon and his colleagues noted several



Doppler shifts of the moving spectral lines of SS433, plotted as a function of time. The experimental points are from several different observations and observatories. The sine curves are fitted to the data with a period of 164 days. (The figure is adapted from references 3 and 5.)

spectral lines that shifted dramatically but continuously from night to night.

Several mechanisms for producing the enormous, variable line shifts were suggested. Thus, for example, Zeeman splitting of the lines in an enormous but variable field was considered a possibility. (A white dwarf has been observed with such splittings.) James Liebert, Roger Angel, E. K. Hege and Peter Martin at the Steward Observatory of the University of Arizona, together with W. P. Blair of the University of Michigan, measured² the circular polarization of the emissions from SS433 and found it to be negligible. An intense magnetic field is therefore unlikely. On subsequent examination, the shifting lines appeared to consist of two sets of Balmer lines, one shifted to the red by varying amounts, the other symmetrically shifted to the blue. Interpreted as Doppler shifts, the changes in wavelength indicated speeds up to 50 000 km/sec and accelerations up to 1000 km/sec per day. The symmetry and regularity of the motion of the spectral lines also helps rule out a magnetic origin.²

The continuum radiation from SS433 is reddened by interstellar absorption. By examining the absorption lines in the spectrum and comparing them with lines in the spectra of stars whose distance is

known, the observers concluded that it is a distant but galactic object, at least 3.5 kpc (11 000 light years) away. Examination of plates taken as far back as 1947 showed very little proper motion of SS433.

Margon, Ford, Steven Grandi and Stone have combined their data with those from several other observers to obtain a fairly complete record³ of line shifts starting in June 1978, shown in the figure. The periodicity and symmetry of the shifts is obvious. The kinematic origin of the shifts is further supported by the fact that all the lines of the red-shifted and the blue-shifted systems can be fitted with Doppler shifts for the two (approaching and receding) speeds. The period deduced from the collected data is pretty nearly 164 days.

Elaine Gottlieb and William Liller of the Harvard-Smithsonian Center for Astrophysics have examined images of SS433 on the plates of the Harvard collection. They found that the blue magnitude of SS433 is variable since about 1929, and that the variations fit the roughly 160-day period found from the recent data.

The identification of the periodicity is not conclusive, Katz told us, and Margon added that more data would be very use-

ful to determine whether the overall brightness changes along with the spectrum—it would make a good project for an amateur astronomer with a 12-inch telescope.

The kinematic model, including the now-obvious periodicity, was proposed⁴ by M. Milgrom, at the Weizmann Institute, on the basis of early, sketchy data, and, independently, elaborated⁵ by Margon and George Abell at UCLA in the light of recent data. In the model, the moving lines are due to radiation from two beams of hot matter ejected in opposite directions from a central object. These beams are well collimated and monoenergetic (to account for the narrowness of the observed lines), and the radiation arises from a small region on the beams, away from the central object.

Fitting the Doppler shifts expected from such a model to the observations shows that the beams are moving with $0.27c$ (81 000 km/sec). The nearly sinusoidal curves are noticeably shifted from the $v = 0$ axis; although the implied speed is large (11 000 km/sec)—compared with, for example, the escape velocity from the galaxy (200 km/sec)—the shift can be entirely attributed to the transverse Doppler effect, and requires no additional gravitational or cosmological explanation. The beams rotate about an axis, thus describing a cone in space. The fit to the data includes values for both ϑ , the opening angle of the cone, and i , the inclination of its axis with respect to the line of sight. One of these is 78° and the other is 17° , but the analysis can not distinguish which is which.

John McGraw, Sumner Starrfield (Steward Observatory) Nathaniel Carleton (Harvard) and Angel, have used high-speed photometry at the Multiple-Mirror Telescope on Mount Hopkins and at the Steward Observatory to look for short-term variations in the output of SS433. Thus far they have found none, indicating that there are no flickers or flashes in the emissions, at least not in the 1–10 sec range that they have analyzed so far. This indicates, McGraw told us, that one is not seeing the sort of flickering emission associated with accretion onto a compact object.

The physics behind the behavior of SS433 is still completely puzzling, Margon told us. The narrowness of the emission lines indicates that the beams are well collimated and that the emitting regions are fairly cool, about 10^4 K, corresponding to thermal energies of about 1 eV. The kinetic energy in the beams is, however, about 30 MeV per particle. Whatever process accelerates the beams must thus produce a very narrow velocity range in addition to a well-collimated beam.

The kinetic energy in the beam is enormous, Margon told us, while the light output is quite small. Thus the accelerating mechanism must also be extremely efficient at producing only the particle

beams with almost no associated radiation: The output of kinetic energy, based on one simple model of the beams, is greater than the output of the Crab Nebula by a factor of at least 10 and perhaps 500, Margon said. (In the Crab, the kinetic energy of the pulsar is converted to the luminous output of the nebula. In SS433 some mysterious process produces only kinetic energy with no luminous output to speak of.)

Most of the theories in the literature were constructed before the recent data were available, and they are not borne out by the data. Katz, a theorist at UCLA, told us that the most likely mechanism for producing the beams involved a dense plasma (density roughly 10^{19} particles/cm³) at temperatures of 10^7 K (about 1 keV thermal energies). The collimation can arise by ejection normal to a planar object, such as the accretion disc around a compact object (black hole or neutron star). Precession of the axis of the accretion disc would give rise to the observed periodicity. The model is like one proposed by James Roberts of UCLA (now at Caltech) for Hercules X-1, Katz said.

Weak magnetic fields in human body

The ability of SQUID (Superconducting Quantum-Interference Device) magnetometers to measure magnetic fields weaker than 10^{-9} gauss has made possible the study of the very weak magnetic fields induced in human beings by biochemical current flow or by the presence of small quantities of ferromagnetic contaminants. The SQUID is basically a superconducting loop with a weak link that behaves as a Josephson junction. One can monitor the intrusion of individual flux quanta ($h/e \approx 2 \times 10^{-11}$ gauss-meters²) as they force their way through the weak link into the superconducting loop. The first SQUID magnetometers were built in 1967 by James Zimmerman and his colleagues at the Ford Scientific Research Lab.

The well-known alpha waves of the human electro-encephalogram (EEG) are accompanied by magnetic waves whose amplitude just outside the skull is about 10^{-8} gauss. An order of magnitude weaker still are localized magnetic responses of the brain to tactile and visual stimuli. Samuel Williamson, Lloyd Kaufman and their colleagues at New York University have recently been studying such neuromagnetic responses. They find that the magneto-encephalographic (MEG) response is sufficiently local that one can distinguish between the brain's response to the stimulation of the thumb and the little finger.¹ In contrast to the EEG response to such a stimulus, the MEG response is observed only on the side of the brain opposite to the stimulus. With regard to visually evoked neu-

Even if such a model turns out to be valid, there are many puzzles left to be explained, ranging from the source of the energy in the beams, to the localization of their emitting regions. There is also, Margon added, the fact that no one has yet observed any interaction of the beams with the interstellar gas. There is clearly much work to be done before the system is understood. For example, he said, a significant part of the precession period has not yet been directly observed, and the data already appears to show deviations from purely sinusoidal behavior for the Doppler shifts. —TVF

References

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romagnetic responses, they report evidence² that the brain's response time varies with the spatial characteristics of different visual patterns. This may be an important clue to the nature of visual perception.

David Cohen, Satoaki Arai and Joseph Brain have been studying the lung's clearance of inhaled ferromagnetic powder in Cohen's magnetically shielded room (see *PHYSICS TODAY*, August 1975, page 34) at the MIT Francis Bitter Magnet Laboratory. In May they reported³ their conclusion that the long-term clearance mechanism of the lungs of heavy smokers is severely impaired. This may explain why smokers are particularly susceptible to carcinogenic atmospheric pollutants other than tobacco smoke. Cohen has also recently published,⁴ together with Neil Cuffin, a detailed computer model comparison of MEG and EEG responses to various current-source distributions in the brain, concluding that the MEG is capable of higher spatial resolution than is the EEG.

Magnetic fields generated by the central nervous system were detected⁵ in 1968 in an early version of the MIT shielded room, but detailed studies at MIT and other labs had to await the development of SQUID magnetometers. A nerve signal is basically a traveling polarization of the membrane surrounding the nerve fiber. This time-dependent polarization behaves like a traveling current-dipole source along the nerve fiber, and generates return currents in the surrounding