SS 433: A New Extraordinary Object in Astrophysics

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During the month of October 1980, theoretical and observational astronomers of many nations gathered in Rome to attend an international meeting, sponsored by the Accademia dei Lincei, with the title "SS 433: A New Extraordinary Object in Astrophysics". It was no aberration that this colloquium was devoted to the study of a single object, as the star in question is certainly the most peculiar object discovered in the sky for several years. In the past few decades, many new types of celestial object, quasars, pulsars and possibly black holes ... have been revealed: SS 433 is no less important, as its properties make it quite unique.

Through the telescope, SS 433 appears as a source of light of 15th magnitude: i.e., about 4000 times fainter than the faintest stars one can observe on a clear night. It lies in the constellation of Aquila, close to the galactic plane, in a region rich in stars and gas and dust clouds. Twenty years ago, following its observation by the American astronomers C.B. Stephenson and N. Sanduleak, it was included in a list of some hundreds of stars that showed hydrogen emission lines, which usually indicate the presence of an extended envelope of gas around the stellar body. The number given was 433 from whence its name. No other spectacular object has been found in the same list from among the many stars of several well known classes.

Subsequently, SS 433 was found and lost several times by astronomers working at different frequencies beyond the conventional "optical" region; e.g., a source of radio waves and X-rays was reported at its position in some Catalogues compiled from observations, that were both ground based and from satellites like Uhuru and Ariel 5, although positional accuracy was poor. Great attention to SS 433 was finally drawn in 1978, after the work of Canadian and British researchers, who reported a high time variability and a non-thermal emission mechanism. The precise position associated with these measurements, allowed the source to be identified with the star SS 433, and this prompted optical astronomers to study its visible spectrum. The first detailed spectrogramme, obtained with the large Anglo-Australian Telescope, revealed unusual properties and provided further confirmation of its identity. However, a radio and X-ray emitting star was not completely new, several such objects being known already.

Other groups of astronomers, Ciatti, Mammano and Vittone at the Asiago Observatory in Italy, and Margon with several collaborators at the University of California, observed SS 433 in the Autumn of 1978 and found quite strong emission lines at unusual positions, defying identification with the elements usually found in stellar atmospheres. Furthermore, changes in intensity and wavelength were evident from one night to the next. For this reason, a systematic effort was made to follow the variations with time, until the star became too close to the Sun.

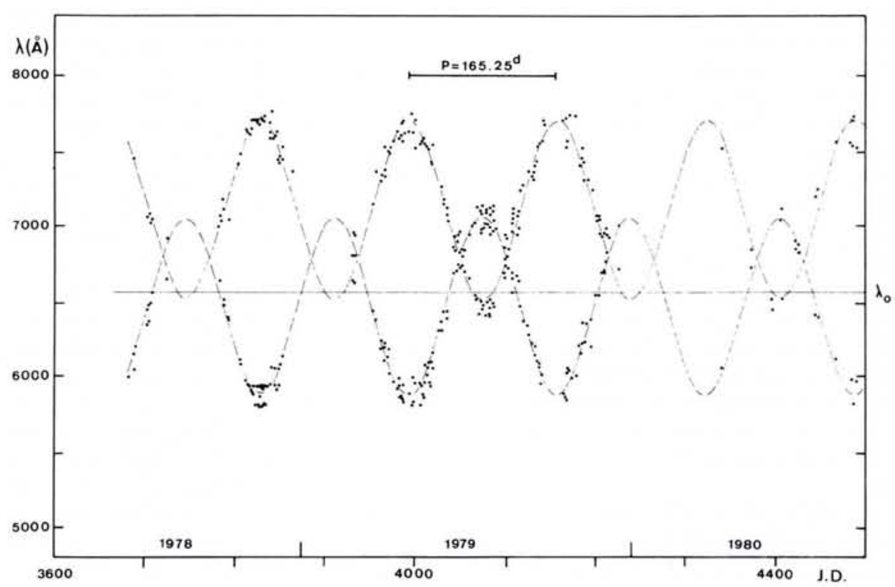
Finally the essential features became clear: in SS 433 the strongest emissions (due to hydrogen and neutral helium) present a triple set of lines: one of them is stationary, near the laboratory wavelength, while the other two are moving on both sides across the spectrum. The wavelength variations cover a complete cycle in a period of about 165 days, describing a sinusoidal curve of unprecedented amplitude (Fig. 1). For instance, the H_α line (λ_o = 6563 Å) has two "satellites" which reach a maximum separation of about 900 Å (one at 7700 Å in the near infrared, the other at 5800 Å in the yellow region). Similar effects are recorded for the fainter features around other spectral lines. In particular, all the satellites are blue- and red-shifted by the same amount $\Delta\lambda/\lambda$ at a given time, which is one of the main reasons for interpreting the effect as due to a Doppler shift ($\Delta\lambda/\lambda \cong v/c$).

The simultaneous presence of a red- and a blue-shift implies that we are observing two emitting regions, one of which is receding and the other approaching the observer. Moreover such large shifts require a very high value of the velocity-up to one quarter of the speed of light, and by far the highest value ever observed for any object inside our Galaxy.

Twin Jets Model for SS 433

The most popular and widely accepted model of SS 433 supposes that two beams of matter are ejected from a central object in opposite directions at high velocity. This interpretation was first proposed by the astrophysicists A. Fabian and M. Rees in England, and M. Milgrom in Israel. Their considerations, based on the first scanty data, still remain the basis of the model which has since been developed by other authors. As the observed spectral features are rather narrow, with only a small velocity dispersion, we must accept that the two beams are well collimated: an angle of the order of 5° being required for the cones of emitted matter. Moreover, in order to explain the sinusoidal motion of the "moving" lines over 165 d, we need a modulation of the radial velocity with such a period. This we deduce is caused by the ejected beams tracing out a cone as they rotate around a fixed axis. In this way the projection of the beam velocity on the line of sight and so the recorded wavelengths change with time.

Fig. 1 — Red- and blue-shifted systems of "moving" lines around H_α (λ_o = 6563 Å) in SS 433, according to the Asiago observations and other published data. Dashed lines indicate the best fit sinusoidal solution. Note the large amplitude, and the red-shift at the crossing points due to the relativistic time dilation in matter moving at $v \cong c/4$.



The motion of the jets from SS 433 is a precessional one, like that described by the Earth's rotational axis, and somewhat resembles that of water from a garden sprinkler. It is also important to note that the two sinusoidal curves do not cross over the stationary lines at zero velocity. The curves are bodily shifted to the red, as can be seen from computing the "barycentric" position of the blue- and red-shifted features for each date. This additional red-shift remains roughly constant with time, and amounts to more than 200 Å at H_α. It can be entirely explained by the so called transverse Doppler effect caused by relativistic time dilation, which makes moving clocks tick slower (commonly described in the "twins paradox"). In our case the clocks are replaced by the emitting atoms which are moving at high velocity, so that the spectral lines are recorded with a shift of about $\Delta\lambda/\lambda = (v/c)^2/2$, quite apart from the radial velocity contributions.

Adopting the model of the precessing double jet, a kinematical analysis of the system has been carried out at Asiago covering data taken also by different observers on 235 nights during 1978-80. The motion of the spectral lines is exactly described by two sinusoidal curves:

$Z_{red} = C_1 + A\cos\phi$ and $Z_{blue} = C_2 - A\cos\phi$

where $Z = \Delta\lambda/\lambda$, and the suffix indicates the direction of shift at maximum amplitude.

The angle formed by the direction of the jets with the line of sight ψ is derived from the expression

$\cos\psi = (\cos i \cos\theta + \sin i \sin\theta \cos\phi)$,

where i is the inclination to the line of sight of the axis of the precession cone, and θ is the aperture. The ambiguity between these angles is resolved later. A least squares fit of the data yields the following "average" parameters.

Period $P = 164.7 \pm 0.2$ days;
$\beta = v/c = 0.256 \pm 0.002$;
$i = 78.6^\circ \pm 0.2^\circ$;
$\theta = 20.2^\circ \pm 0.3^\circ$.

The qualification "average" is necessary as an evident variability is observed, in both the intensity and shift, which does not always fall on the predicted curve but oscillates round it without any apparent regularity. The lines are found inside a band about 100 Å wide, and often they have a complex structure; two may appear in the red or blue system, and sometimes also in both. This well-established finding might suggest that more than one pair of moving elements is responsible for the observed behaviour. Moreover, a kinematical analysis carried out night by night allows us to conclude that the ejection occurs with varying velocity, in the range from 0.2 to 0.3 c. Also the orientation deviates from the predicted by up to 6-7°. We are thus led to conclude that some perturbations affect the ejection mechanism, making it more complex than assumed in the simple model.

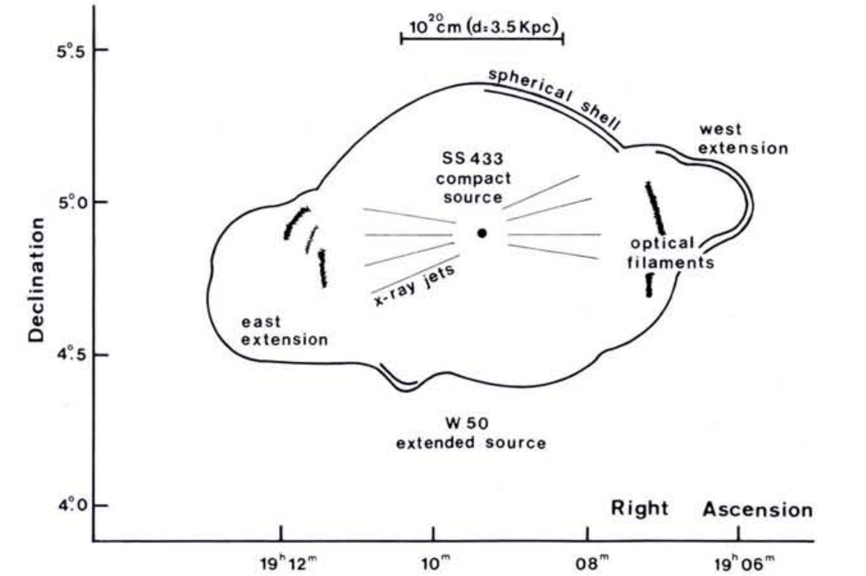


Fig. 2 — Schematic picture of SS 433 inside the radio supernova remnant W 50. Its extensions, optical filaments, and the extended radio and X-ray structures elongated in the same direction, support the model of double beam ejection.

In particular it seems clear that matter is not flowing away from SS 433 continuously, but rather as discrete clouds of gas, like "bullets", each of them emerging with a particular velocity and at a somewhat unpredictable angle. Two or more pairs may be in evidence at a given time. An interesting feature is the persistence of spectral features at a given wavelength for typically 3-4 days, during which time the line intensity generally fades away. These data are consistent with an individual bullet, having an emission length of some 10^{13} m and moving at constant velocity. Some consideration of the emission mechanism also indicates typical dimensions of 10^{10}-10^{11} m for the largest bullets, and a density of the order of 10^{10} n_e cm^{-3}.

A particular type of deviation from the smooth predictable motion of the lines is a symmetric variation of both blue and red curves. Over a few days the two shifts change by 100 Å with mirror-image symmetry. This phenomenon has been recorded several times, and it seems to be related to a particular phase in the 165 d period. One first conclusion is that the antisymmetry in the spectrum is caused by a single physical mechanism, producing simultaneously the same ejection and acceleration on opposite sides of the central object.

SS 433 as a Stellar Supernova Remnant

Having described the unusual phenomena seen in SS 433, let us consider its location in the sky. Radio maps of the area indicate the presence of an extended source of shell structure and with roughly elliptical shape (1° x 1.5°). Observations at different frequencies indicate non-thermal radio emission from this source that was named W 50. It is thought to be a supernova remnant, although it is not typical, as strong emission is produced also in the inner regions. The radio data indicate a distance of 3-4 x 10^3 parsec (1 pc = 3.26 light years $\cong$ 3 x 10^{16} m) in good agreement with independent estimates obtained from the study of interstellar absorption lines in the optical spectrum of SS 433.

This coincidence strongly supports the idea of a physical connection between the two objects. Moreover SS 433 is located very close to the centre of the extended source. In this case, we interpret the peculiar object SS 433 as the stellar remnant (a neutron star, or possibly a black hole, depending on the mass of the progenitor) of a supernova which exploded a few 10^4 years ago. This age can be deduced from the radio brightness and dimension of W 50, if we adopt the usual model for the expansion of a supernova shock wave across the interstellar medium. W 50 thus would be one of the oldest supernova remnants we observe, whereas the collapsed star in it would be relatively young, when compared with other members of X-ray emitting binary systems. Only in the Crab Nebula and in Vela are neutron stars (pulsars) of lesser age observed.

Other remarkable features of W 50 can be considered as further support for the model of a double jet from SS 433. First of all its shape could be interpreted as the overlap of a circular region, centred on SS 433, and two extensions to the east and west (the ansae, or "ears"). The orientation and width of these extensions on both sides are in good agreement with the idea of an interaction process taking place between the relativistic jets and the surrounding, previously symmetric envelope, created after the supernova event. In the same directions some faint filamentary nebulosities have been optically observed, which are barely visible on the Palomar Sky Survey plate. Whereas some authors have also suggested the possibility that W 50 may result from the same activity as SS 433 (that is not necessarily implying a supernova for its origin), the analysis of the optical spectrum (consistent with excitation by shock in a pre-compressed matter) and the morphology of the filaments, favour the supernova remnant hypothesis. This allows us to solve the ambiguity between the angles i and θ. The picture is indeed consistent with ejection occuring around $i = 78°$, close to the plane of the sky, and with an aperture $\theta = 20°$.

Other evidence for the reality of the jets is given by observations of the radio source SS 433 at the high resolution now attainable with VLBI (Very Long Base-Line Interferometry) techniques using linked radio telescopes. The radio emission comes from a compact core (less than 0.1″) and an elongated structure (2″, that is 10^{15} m overall and at a distance of 3.5 kpc) which is interpreted as the double beam of relativistic matter, at a distance greater than the optically emitting region. Its position angle coincides with the direction of the extensions and filaments in W 50. Moreover, it has been possible to follow changes in the position angle of the radio source from 78° to 118°, in agreement with the precessional motion occuring in the 165d period. Also, the outward motion has been followed with time for some discrete blobs, ejected at different times, each propagating with constant direction.

To add to this, SS 433 has been observed with the new Heao-2 (Einstein) satellite, which is the most recent X-ray observatory, of good sensitivity and positional accuracy. The source consists of a core of 3″ coincident with the star (with luminosity of the order of $L_X = 10^{28}$ J/s), and fainter features extending at least up to $\pm$ 25′ from the central source (about 10^{18} m) in the same direction as the radio jets. These extended X-ray cones are produced by the outflowing matter over some hundreds of years, and are thus fairly wide since the precession effects are smoothed out. Their width is possibly less than $2 \times \theta = 40°$ as if the trajectories were not ballistic, owing perhaps to the interaction with the ambient medium that produces the X-ray emission. The characteristic features, discussed in this section, are sketched in Fig. 2.

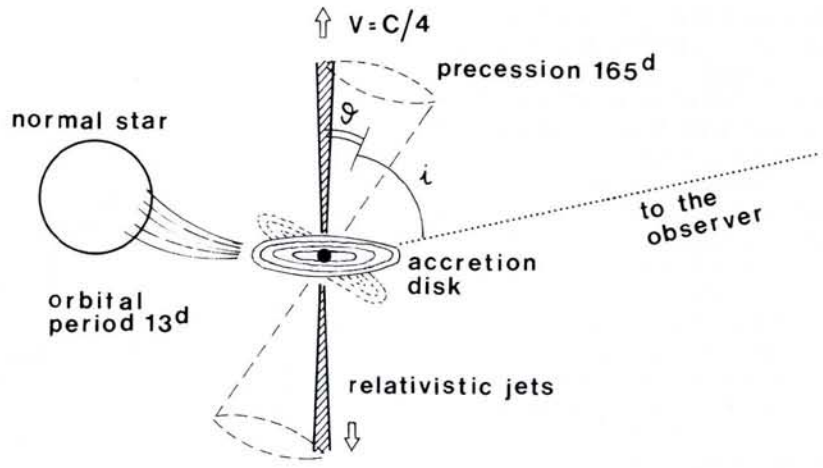


Fig. 3 — Possible model of SS 433 in binary system, with the relativistic jets outflowing from a thick accretion disk undergoing precessional motion.

SS 433 as a Binary System

A careful study of the stationary lines, first neglected, has been carried out at the Dominion Observatory in Canada. It has revealed a clear wavelength oscillation with a period of 13.2d indicating small radial velocity variations (of the order of $\pm$ 73 km/s). Photometric observations secured by several groups have also shown a modulation with the same 13d periodicity, superposed on other irregular light variations.

The mean light curve has a double peaked shape, with total amplitude of about fifty percent in the visible band. One difficulty in discussing these data is that we are not sure where the stationary spectrum originates from: the companion star, gaseous streams, an accretion disk, or even a large region around the whole binary system. Taking into account the distance to SS 433, and the high obscuration in that direction inside the Galaxy, we obtain a rather high total optical luminosity, of the order of $M_V \leq -5^{mag}$ ($L_{vis} \cong 10^{30}$ J/s) like that of an upper main sequence star of the 0 class. Adding the photometric data (similar depth of the two light minima), it seems that both components in the system are of comparable brightness.

Another periodicity which coincides with that of the precessional motion (165 d) concerns the line intensities and the total luminosity. These reach their maximum and minimum when the lines are respectively furthest apart and nearest together. In a model involving a bright star and an accretion disk of similar brightness, this dependence would result from the varying orientation of the disk. The disk would be almost face-on at maximum separation of the moving lines, edge-on at their crossover, while the ejection of the relativistic jets would occur along an axis perpendicular to the plane of the disk (see Fig. 3).

An accretion disk forms in the presence of binary mass transfer, as the angular momentum of the accreting matter prevents radial infall on to the companion. Material in the disk that is produced, dissipates momentum by spiralling inwards. This is found in many astrophysical objects such as dwarf novae and X-ray emitting binaries. In our case, the mass loss may, in principle, be provoked by the strong stellar wind from the bright companion star. Accretion is likely to occur at a supercritical rate, which would favour the formation of a large and thick disk and from this aspect, SS 433 turns out to be not so different from other known binaries with a collapsed component, although its X-ray luminosity is smaller by two orders of magnitude. There remains, however, the unique presence of the twin jets.

Despite the intensive and fruitful obervational efforts made over the past two years, many questions about the true physical nature and evolutionary phase of the object, are still open, and despite intensive theoretical work the source of the huge amount of energy required for the beam ejection and acceleration, estimated to be not less than 10^{31} and possibly 10^{33} J/s, is not known.

It is peculiar that the relativistic gas is seen only through spectral lines of low excitation like those of HI and HeI. Other questions concern the sharp collimation of the beams (for which magnetic fields, or funnelling along the rotation axis of a thick disk, have been suggested) and the origin of their 165 d precession. For this latter, several alternative explanations are proposed, including free precession of the neutron star, relativistic Lense-Thirring precession of the compact object with a massive rotating disk, or motion of the plane of the disk, either driven by the companion star misaligned with the binary plane ("slaved disk") or itself precessing under tidal forces ("master disk"). Of them all some type of disk precession seems more appropriate as it can explain the photometric variability and the observed irregularities in beam direction.

Many of these questions are connected with the nature of the central object. Is this a neutron star, or a more exotic black hole? Some of the proposed models for SS 433 postulate indeed the presence of a black hole, and the ejected beams are replaced by a ring of matter around it. In the ring, a high keplerian velocity is attained, and the emission from two opposite points reproduces the observed curves for the moving lines.

Such a ring would have to be small, and one has then the difficulty in these models of explaining the high luminosity in the lines, unless thermal emission is replaced by a coherent (lasing) mechanism. Also the low temperature in the relativistic regions puts constraints on their distance from the central source, which in turn would require a very high mass for the black hole. More-would be a young active neutron star, orbiting around an early type evolved companion, accompanied by a thick accretion disk. In this scheme, the effects of a systematic time delay for the light travel should be observable between the two emitting regions. Variations should indeed first be recorded from the blue-shifted system, formed closer to the observer, and the delay between the two systems should vary systematically throughout the 165d period. Although this is not clearly visible in the described line variations, an analysis applied to the whole sinusoidal curves seems to indicate that statistically significant differences do exist. A separation between the two regions of the order of $\pm$ 345 astronomical units ($\pm$ 5 x 10^{13} m) has been indicated, but with a still rather high associated error.

Double Jets in Other Astrophysical Objects

The probable presence of a double jet from SS 433, besides its obvious intrinsic interest, could be stimulating for the study of very different objects, like galaxies of quasars which present two extended and opposite radio lobes. The formation of such lobes is also interpreted in terms of the ejection of high speed particles, but on a much larger energy and dimension scale. Anyway, the possibility is now eagerly being studied that SS 433 may be a reduced version of the same process. If a single mechanism could be established which can work at different scales, SS 433 would help in understanding the nature of the ejection phenomena from active nuclei of galaxies.

SS 433 remains for the present unique. Only one candidate source, CIRCINUS X-1, shows radio, X-ray and optical emission but the signature of relativistic motion is missing. Other sources nevertheless deserve further study. If SS 433 really is an early phase in the evolution of a binary system with a collapsed component, its large energy and mass requirements would imply that this phase of its evolution would necessarily be short lived. It may therefore be the rare example of a still undetected phenomenon.

In the relatively short time since the discovery of its extraordinary properties, SS 433 has already been the subject of more than 150 papers and scientific communications. If the observational and interpretative efforts continue with the same intensity over the next years, we may reasonably hope to obtain a better insight into its physical nature and disclose the mechanism which makes this star so unusual and exciting.

European Journal of Physics

Editorially, Volume 1 of the *European Journal of Physics* is complete and Number 4 should be published in the very near future. To show more clearly the scope of this journal of the European Physical Society, aimed at physicists in the higher teaching establishments, we reproduce below the titles of the articles in Numbers 3 and 4 (omitting the regular features such as News, Book Reviews and Letters).

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J.-P. Swings, Cointe-Ougrée, B
M.Q. Tran, Lausanne, CH

Category 4C

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Bulgarian Academy of Sciences
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