THE STAR OF GREATEST KNOWN MASS

By J. S. Plaskett

Introduction

I HAVE been asked by the Editor to write for the Journal a short account of the very massive binary system recently investigated at Victoria. A paper on this star was presented to the Royal Astronomical Society and read at the June meeting, and this appeared in "Monthly Notices" for June. The complete spectroscopic orbit with observational data and discussion appeared in Vol. II, No. 4, Publications of the Dominion Astrophysical Observatory, and the only purpose of this article is to present in as non-technical language as possible for the many amateur readers of the Journal an authoritative account of what is known and can reasonably be deduced about this interesting system, especially as in the wide newspaper interest and publicity, entirely unsought by the writer, some erroneous conceptions have probably appeared.

After the completion of the first radial velocity programme of the observatory, it was deemed desirable, before undertaking another extensive programme, to complete some special investigations which appeared of importance and interest. Consequently Mr. Harper and Dr. Young undertook the determination of absolute magnitude and spectroscopic parallax of the stars observed here for radial velocity, Mr. H. H. Plaskett worked on intensity distribution in stellar spectra and on the physical interpretation of the spectra of O-type stars, while the writer decided to investigate the radial velocities of the absorption line O-type stars.

Stars of this spectral type are relatively few in number in the sky, less than one-tenth of one per cent., are strictly confined to certain parts of the Milky Way and are hence interesting on account of their rarity and their probable exceptional nature. They are distinguished by being the very hottest of the stars and by the presence in their spectra of lines due to the ionized atoms of helium, nitrogen, silicon and other non-metals. Among those already investigated the proportion of spectroscopic binaries was found to be higher while the spectroscopic orbits completed gave greater masses than in any other spectral class. One of the main reasons for investigating their radial velocities as a class was to determine the mass ratio wherever possible. I am indebted to the kindness of Miss Cannon in the preparation of the observing list which contains 49 stars, all the known Oe and Oe5 stars, 36 in number, within reach in declination at Victoria and sufficiently bright for spectroscopic observation with the 72-inch telescope. Thirteen others suspected for various reasons of being similar in type were included.

Orbit and Mass of System

The star B.D. 6° 1309, No. 2422 of the Harvard Revised Photometry and No. 47129 of the Henry Draper Catalogue, R.A. 6h 32.0m, Dec.+6° 13′ (1900), visual magnitude 6.06 is one of the additional suspected stars furnished by Miss Cannon. Its spectrum is classified as A5 in Harvard 50 but as Bop in the Henry Draper Catalogue, and in the remarks it is stated "Hβ is not seen as a distinct dark line and appears to be slightly bright. The lines are narrow. Line 4200.3 is strong". The first spectrum obtained on December 6th, 1921, showed doubled spectrum lines of spectral type about Oe5. As there was wide separation of the doubled lines this one spectrum was sufficient to show that the velocity range was unusually large and that the system was probably of great mass. Consequently spectra were obtained as frequently as possible, and by April 5th, 1922, when the star was getting pretty far west for observation, 30 spectra, sufficient to determine the orbit, had been secured.

The spectrum is different, although not markedly so, from any other O-type spectrum obtained and would be classed as about midway between Oe and Oe5. It contains strong lines of the Balmer Series of hydrogen, of the Pickering Series of enhanced helium and fair lines of enhanced nitrogen and enhanced silicon. The lines of ordinary helium are rather weak and there are traces of magnesium 4481 of oxygen and of carbon. The H and K lines of calcium which frequently behave abnormally in these high temperature stars are abnormal in this star, being sharp and very strong and not sharing in the velocity displacements of the other lines. There are traces of emission lines or bands in the spectrum but many of the O's are similar in this regard. Were it not for the doubled lines and large displacement, there is nothing in the spectrum to indicate the extraordinary character of this system. The spectrum of the fainter component appears to be quite similar in type but weak and diffuse so that the velocity measures are difficult and uncertain. Consequently the elements of the spectroscopic orbit were obtained from the spectrum of the brighter component and the measures of the fainter only used to determine the total range of its velocity, necessary to obtain its mass.

After a dozen or so observations had been obtained it appeared as if the period was about 15 days and as, with the velocity range observed, this would mean a mass of over 100 times the sun, much larger than any previously obtained, observations were obtained as frequently as possible to check up this period. Further as it has been found here on two or three occasions that apparently long period binaries, on further analysis were shown to have periods slightly less or greater than a day, two observations per night, as widely separated as possible, were made on four nights. These duplicate observations and further trials with all the 30 measures showed conclusively that the period could not be near a day and there can be no doubt that the period obtained, 14.414 days, is the correct one. When the observations are plotted with this period as shown in the velocity curve, Fig. 1, all the residuals are satisfactorily small, the probable error of the velocity measure of a single plate being only about 5 km. per sec. The chance that the period is other than that found is hence negligibly small.

The spectroscopic orbit was determined in the usual manner from the twice measured observations and was corrected by least-squares resulting in the following elements:

Period	P	$= 14.414 \pm 0.016$ days
Eccentricity	e	$= 0.035 \pm 0.011$
Longitude of Apse	ω	$= 181°.95 \pm 2°.54$
Time of Periastron	T	$= 2{,}423{,}031.870$ J.D.
Velocity of System	γ	$= +23.94 \pm 1.4$ km.
Semi-amplitude Primary	K_1	$= 206.38 \pm 1.95$ km.
Semi-amplitude Secondary ..	K_2	$= 246.7$ km.
Projected Semi-Axis Major ..	$(a_1 + a_2) \sin i$	$= 89{,}750{,}000$ km.

As previously indicated these elements were obtained from the measures of the primary spectrum and only K_2 was determined from the uncertain measures of the secondary.

From the usual formulae we obtain the following masses, always, however, containing the factor of the cube of the sine of the inclination of the orbital plane, which is indeterminable in spectroscopic binaries, and the resultant figures are hence minimum values of the masses.

$$m_1 \sin^3 i = 75.6 \odot$$

$$m_2 \sin^3 i = 63.3 \odot$$

$$(m_1 + m_2) \sin^3 i = 138.9 \odot$$

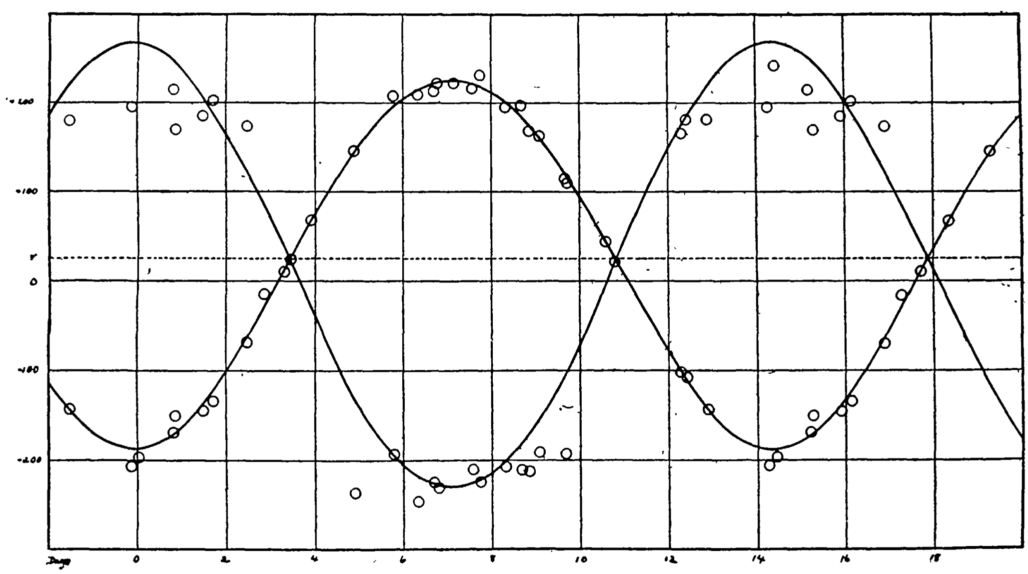

Fig. 1

It may be of interest to look at the determination of the masses in a different way. What is generally called the harmonic law offers a simple method of determining the masses of any revolving system. This law states that the combined mass of any such system is to the combined mass of a second system as the cube of the separation divided by the square of the period of the first system is to the cube of the separation divided by the square of the period of the second system, or $m_1 : m_2 = \frac{a_1^3}{p_1^2} : \frac{a_2^3}{p_2^2}$.

By taking the sun-earth system as the standard we find that these two stars revolve around one another neglecting the inclination of the orbit plane, at a separation of 89,750,000 kms. or .6003 the sun-earth distance in a period 14.414 days or .03946 years. Hence the mass of the system is

$$\frac{.6003^3}{.03946^2} = 138.9 \text{ times that of the earth-sun}$$

and as the mass of the earth is only about one three hundred and thirty thousandth of the sun it can be neglected and we get as before what might be called the projected mass $(m_1+m_2)\sin^3 i =$ 138.9 times the sun.

The mass is certainly greater than this value, for as will be seen later the diameters of these stars are probably about 20 and 18 times the sun and they are separated about 65 solar diameters. If the plane of revolution were nearly in the line of sight, the two stars would mutually eclipse every revolution, and we would have an eclipsing variable. As the variation of this naked eye star has not been observed, it is unlikely they eclipse and a simple calculation shows the orbit plane must be at least 17° from the line of sight or $i = 73°$. At this inclination $\sin^3 i$ becomes 0.875 and the masses must be at least 14 per cent. greater making them 86 and 72 respectively and the total mass nearly 160 times the sun. If any inclination is considered equally probable the average value of $\sin^3 i$ is about 0.6 making the average value of the mass about 230 times the sun. It is perhaps a reasonable assumption, however, that the plane of the orbit is not markedly different from that of the Milky Way in which the star is situated, and hence that the value of 160 times the mass of the sun, more than four times greater than any previously determined, is the most probable. However, in the deductions to follow the actual computed values will be used.

Probable Brightness and Distance of System

It will be of interest to deduce from the known dimensions of this system as given by the spectroscopic orbit, the absolute magnitude of the two stars and hence from their apparent magnitude, the parallax or distance. Two methods of attack are open to us. The first is entirely theoretical, developed by Eddington* from considerations of the radiation pressure and the absorption in the

*Ap. J. 48, 211.

interior of a star, from which he deduces that the total radiation of a giant star is, for a given mass, inversely proportional to its opacity and otherwise independent of its density or stage of evolution. He obtains expressions from which the absolute magnitude for any mass can be obtained. From these formulae the absolute magnitudes become for

$$m_1 = 75.6 \odot \qquad M_1 = -6.25$$
$$m_2 = 63.3 \odot \qquad M_2 = -6.03$$

These are balometric magnitudes and to reduce to visual magnitudes requires for stars of this spectral type and temperature the addition of about +0.6 magnitudes, making absolute magnitudes in the usual units −5.65 and −5.4 and the total magnitude of the system −6.3.

The second method depends upon estimates of the surface brightness and surface area of the stars. Several determinations of the surface brightness of stars of different temperature or spectral type have been made by Russell, Eddington, Seares and others and the various methods agree fairly well. I have preferred to accept Russell's values as corrected by the results of interferometer measures of stellar diameter* which gives the surface brightness, brightness per unit area, of the Oe star 6° 1309 as about four magnitudes, forty times brighter than the sun. Considerations deduced by H. H. Plaskett in a recent paper† give the probable temperature of a star of similar spectral class to 6° 1309 as about 17000° K, and when this temperature is applied in formulae given by Seares‡ we get a surface brightness nearly the same as above.

With known mass, the density is required in order to determine the surface area. Estimates of the density, however, are subject to considerable uncertainty. We have reliable data of the density of early B's from eclipsing variables where the average density is 0.05 varying between 0.0004 and 0.18. This star is, however, at considerably higher temperature and considerably more massive and radiation pressure should tend to cause it to "blow out", become less dense. The star β Orionis is of the same order of brightness, and probably of mass, as 6° 1309 and some information

*A.S.P. *34*, 92.

†Pub. Dom. A'p'l Obs'y, Vol. I, No. 30.

‡Ap. J. 55, p. 197.

may be obtained from its probable density. The spectral type is B8 and the parallax 0″.007 makes its absolute magnitude −5.5 and it seems safe to assume, with the mass of 6° 1309 in mind, that its mass is 50 times the sun. The apparent diameter computed from Russell's corrected values* is 0″.0019 and this with a parallax of 0″.007 and mass 50 gives a density 0.002 the sun, while a smaller mass would give proportionately smaller density. Probably β Orionis is in the giant stage and the density of 6° 1309 must be greater. These considerations seem to indicate a probable density of 0.01 and as this is confirmed by extrapolating from Seare's values,† the values of absolute magnitude computed from this estimate can not be far from the truth.

With a mass of 75.6 and a density 0.01 times the sun, the diameter of the brighter component of 6° 1309 will be nearly 20 and its surface area 385 times the sun, which with surface brightness −4.0 magnitudes or 40 times makes its absolute brightness over 15,000 times the sun or −5.65 magnitudes. This value is in exact agreement with that obtained from theoretical considerations and while this is of course only accidental, it serves to confirm the substantial accuracy of the deductions, and to clearly show that this is not only the most massive but also the brightest known stellar system.

With a total absolute magnitude of −6.3, 27,000 times brighter than the sun and an apparent magnitude of 6.06 the parallax is easily calculated as 0″.00035, about 3,000 parsecs, 10,000 light years. Although the absolute magnitude is greater than any known system, the conservative estimate of density and the use of the minimum instead of the probable mass points to under rather than over estimate of magnitude.

Stationary Lines of Calcium

There is one other interesting feature about this extraordinary stellar system, the behaviour of the calcium lines *H* and *K*. As is well known in many spectroscopic binaries of the B-type with diffuse lines of hydrogen and helium, the lines *H* and *K* are very sharply defined and have a stationary or nearly stationary velocity

*A.S.P. *34*, 92.
†Ap. J. 55, p. 197.

displacement, not sharing in the oscillatory motions (due to orbital velocity) of the other lines. No satisfactory explanation, which will cover the varying behaviour of these lines in different stars, has yet been adduced and this particular star does not give much assistance in the problem. While the lines of hydrogen, helium, nitrogen and silicon in the atmosphere of the star oscillate back and forward with a range of over 400 kilometres, about 6 *A*, the *H* and *K* lines remain absolutely stationary with respect to the sun, giving a radial velocity of $+16.0 \pm 0.25$ km. per second. The probable error of the determination of the velocity of a single plate from these two lines is only ± 1.35 km. per second. This is remarkably small for single prism observations and shows conclusively that the calcium vapour which produces the lines does not shift its position as the two stars revolve around one another.

Two explanations have been offered for this general phenomenon of stationary calcium lines, one that the binary system has an outer surrounding cloud of calcium which either does not revolve with the system or else at a much reduced rate, and the other that there is an intervening calcium cloud in space. Neither one of these hypotheses suits all the observed cases, and it may be possible that some of the stars with stationary calcium lines have a surrounding cloud and some an intervening cloud or some other explanation may be necessary.

In the case of 6° 1309 it seems hardly possible that two such enormously massive bodies whirling around one another at velocities of over 200 km. per second should not induce some motion, which would be indicated by a radial velocity displacement in any near surrounding cloud. With a surrounding cloud also its velocity should be the same as the velocity of the centre of gravity of the binary system but in 6° 1309 the velocity of the cloud is $+16.0 \pm 0.25$ km. and of the system $+23.9 \pm 1.4$ km., the system receding from the sun 8 km. per second faster than the cloud. This difference would seem to rule out the hypothesis of the surrounding cloud, unless the line displacement equivalent to the 8 km. can be explained by some other cause than velocity. Errors in the wave lengths used and the effects of pressure are entirely inadequate to account for so great a difference, and this seems a case in which the relativity shift, which is in the right direction, might enter.

The three astronomical consequences of the general theory of relativity as stated by Einstein are—

1. The advance of the perihelion of Mercury's orbit.

2. The bending of light in passing near a heavy body such as the sun during eclipse.

3. The displacement of all the lines to the red in the spectrum of heavy bodies such as the sun or stars.

The first two consequences appear to be confirmed but the shift of the spectrum lines in the sun, where it should be equivalent to a velocity of +0.635 km., has not yet been definitely found. As this system is so much more massive than the sun the displacement, which is directly proportional to the mass and inversely proportional to the radius, should be greater. The relativity displacement for the bright component of 6° 1309, the component from which the orbital elements were determined, will hence be, according to the dimensions already obtained, $\frac{75.6}{19.5} \times 0.635 = +2.5$ km. To this is to be added the effect due to the fainter component 130 solar radii distant, +0.3 km., making +2.8 km. The calcium lines would also be shifted in the same direction but the probably great distance of either a surrounding or isolated cloud would make a negligible reduction. The maximum amount of the relativity displacement with the assumed value of the density is, therefore, only 2.8 km. as compared with the difference of 8 km. To have a relativity shift of 8 km. would require the inadmissible density of 0.4 times the sun for this very hot star.

The absolutely stationary lines and this difference in velocity seem to definitely rule out the hypothesis of a surrounding cloud in this star and make the assumption of an intervening cloud more probable. This assumption is strengthened by the curious fact that the velocity +16.0 km. is almost exactly identical numerically with the component in this direction of a solar motion of 20 km. per second. In other words the assumed intervening calcium cloud is stationary with respect to the system of stars from which the solar motion has been determined. A similar relation is found in the case of most of the Novae and in many of the stationary calcium lined binaries and seems to be a fairly general phenomenon giving support to the theory of stationary calcium clouds in space.

Summary

The principal known and deduced facts about this interesting system may be briefly summarized. It consists of two enormous suns, 10,000 light years away, each at a temperature of about 17,000° K., 30,000° F., revolving around one another at a distance of about 90,000,000 km., 55,000,000 miles in 14.414 days. The brighter, more massive of the pair, moves with a velocity of 206 km. about 130 miles per second, is of a mass at least 75 and probably

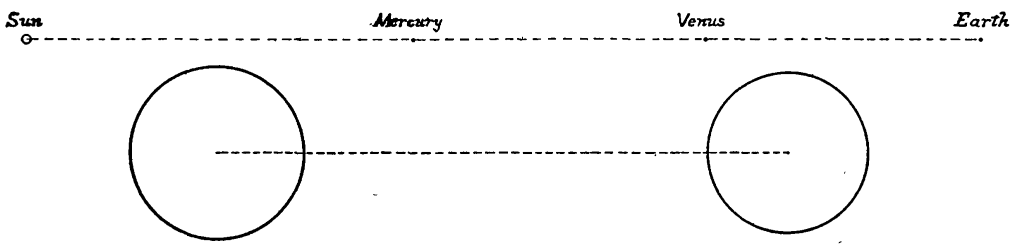

Fig. 2

about 90 times the sun, is 19.5 times the diameter and 15,000 times as bright. The fainter component moves with a velocity of 247 km., about 155 miles per second, is of mass at least 63 times and probably 75 times the sun, is 18 times the diameter and 12,000 times as bright. A graphical representation of the relative dimensions of the system as compared with the sun is given in Fig. 2. The system is moving away from the sun with a speed of 24 km. per second and the spectra show the presence of calcium vapour receding at the rate of 16 km. per second.

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