PHYSICAL PROCESSES IN CYGNUS X-2

ROBERT E. WILSON
Dept. of Astronomy, University of South Florida, Tampa, Fla., U.S.A.

In developing models for the point X-ray sources the general aim has been to find a common explanation for all such objects. However, important observational differences have already become apparent among the systems having optical identifications. A close examination of the evidence shows that those with the most certain optical identifications, Scorpio X-1 and Cygnus X-2, have very few features in common and, in fact, the model proposed here for Cyg X-2 can probably be excluded for Sco X-1.

Except for having generally similar colors, Sco X-1 and Cyg X-2 are decidedly different in almost all observational characteristics. The only lines in the spectrum of Sco X-1 are emission lines, while Cyg X-2 shows many lines in absorption but only one in emission. Cyg X-2 is known to be a spectroscopic binary*, whereas there is no evidence for binary motion in Sco X-1. Furthermore, the proper motion study by Sofia *et al.* [2, 3] points to probable membership for Sco X-1 in the Scorpio-Centaurus association, thus indicating a visual luminosity too low for even a single main sequence star and making it still less probable that the object is binary. Sco X-1 should also be much the younger of the two since the Scorpio-Centaurus association is only about 20 million years old, while the radial velocities of Cyg X-2 are difficult to reconcile with pure Population I kinematics [4], but are quite consistent with the older disk population. In addition Cyg X-2 has many spectroscopic peculiarities which make it not only different from Sco X-1 but unique among known stellar objects. We shall see, however, that it is possible to account for all of these peculiarities with one physically reasonable model. In fact, we shall even find this model similar to a kind of system previously identified from observations of a quite different sort.

Cyg X-2 is the only point X-ray source for which optical spectroscopy has provided really significant information, but it has not been possible to make straightforward interpretations of this information in terms of previously known objects. We briefly state here the basic well established observational facts. The system is a spectroscopic binary [5] with one component a G-star [6]. The distance is probably 500 to 700 parsecs [6], based on an assumed M_V of $+5\overset{m}{.}5$ for the G-star, which determines the X-ray luminosity to be about 25 $L_\odot$. Balmer absorption lines are seen [5, 6, 7], but these could scarcely be associated with the G-star since both their equivalent widths and their half-widths are far too great for any conceivable physical conditions that might be found on a G-star. That is, the equivalent widths correspond approximately to spectral type A8 and the half-widths to a temperature much higher than that needed

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* In a recent paper, Kraft and Miller [1] have given radial velocity observations which, in their opinion, weaken the case for Cyg X-2 being a spectroscopic binary. However, we shall see that if the present model is correct, the lines measured by Kraft and Miller will be very poor indicators of binary motion.

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to completely ionize hydrogen. Sofia [8] has shown that all broadening mechanisms except mass motions can be eliminated, and since these mass-motions must be of the order of 10^3 km/sec, their association with any kind of recognizable G-star becomes still more unlikely. We also have the following additional observations:

(1) The Balmer line ratios are peculiar, with the *high* number lines relatively strong, Hβ weak and Hα absent.

(2) The radial velocity measures, although indicating binary motion, show much greater scatter than can reasonably be attributed to measuring errors.

(3) The Ca II and Balmer line velocities are in general agreement [5, 6, 7] although the Ca II lines are far too strong to be formed in the same region as the Balmer lines.

(4) Peimbert *et al.* [9], have shown that the absolute spectral energy distribution can be fitted by the sum of a normal G-star spectrum and an additional source approximately constant per unit frequency interval. This source makes the *U*, *B*, *V* colors bluer than those of a G-star alone.

(5) There are minute-to-minute fluctuations in optical brightness.

Although we have a diversity of clues into the nature of Cyg X-2, attention must repeatedly revert to one truly remarkable fact, which is that the Balmer lines appear in absorption. We have already seen that the broadening of the Balmer lines can only be due to mass motions of the order of 10^3 km/sec, and we also know that, since Balmer lines arise from an excited level, we should see them in emission rather than absorption unless they are formed immediately above a source of continuum radiation. Thinking first that this source of continuum radiation will be a stellar photosphere, we find ourselves trying to imagine vertical motions of 10^3 km/sec in the outer layers of a star – a situation for which no physical mechanism seems to exist. Convective motions should not approach this magnitude and, since the profiles are symmetrical, we can rule out motions which go only away from the observer, such as might be expected for matter falling onto a star. Falling matter would, of course, produce strongly assymetric profiles. Even if we relax all but the most fundamental physical constraints, there exist very few reasonable models involving mass motions of gas both toward and away from the observer at 10^3 km/sec while interposed between the observer and a star. In an accretion model, we could imagine approximately symmetrical motions being produced by infalling matter if the X-ray luminosity were sufficiently great so that radiation pressure could drive cells of the material back to considerable heights. However, this fails on many counts, such as the impossibility of maintaining hydrogen neutral in such temperature conditions, damping of motions by collisions of gas cells, and several other reasons. We might even picture optically thin material falling onto a compact object, but producing absorption lines because it is seen *projected* against the more distant G-component. This accounts for the symmetrical profiles but must be abandoned because it could only apply during a small phase interval, while the Balmer lines have been seen on all spectrograms of Cyg X-2. Strange as these ideas seem, they are worth mentioning to illustrate the extremes to which one must go to account for formation of the Balmer lines against a stellar continuum.

Of course, there does have to be a source of continuum radiation against which we see the Balmer lines, but from the preceding paragraph it appears that it cannot be a star. We may now pause to recall the various identifiable regions which must exist in Cyg X-2. We know there is a G-star because its spectrum has been observed, and we know there is at least one additional source of continuum radiation because one is required for the Balmer lines and because a source of excess blue radiation is required by the spectrophotometry. There seems to be no reason to doubt that these sources are the same. Finally we expect a region in which the X-rays are formed, which should be a very high temperature region and thus distinct from the other two.

All of these features will be present if the object is a semi-detached binary in which the primary component is a white dwarf accreting material which flows from a G-star secondary through the inner Lagrangian point. The X-rays will be produced at the white dwarf by the accretion mechanism as in the neutron star accretion model proposed by Sklovsky [10] for Sco X-1. We exclude a neutron star for Cyg X-2 because the explosion accompanying its formation would probably disrupt any close binary system [11]. The continuum source against which the Balmer lines appear will be the region of enhanced density in the general vicinity of the white dwarf where the infalling matter has been gravitationally focused. A general picture of how such material will move can be gained by inspection of trajectories computed by Kopal [12]. The trajectories show that the material will fall almost directly toward the white dwarf but, since the star presents a very small target, will not, in general, strike it directly. Once having entered this region of relatively high density, orbital energy will be lost through collisions and eventually the matter must fall onto the white dwarf. At any given time we expect a cloud of relatively high density which will show large Doppler motions due to the complicated gas streaming present. Since the Balmer line widths correspond to velocities of about 10^3 km/sec, the radius of the cloud should be about 10^5 km, for this is the distance from a 1-solar-mass white dwarf at which velocities of 10^3 km/sec are reached in free fall. The continuum radiation is due to heating of the cloud by the large X-ray flux, which should be about 10^{14} erg/cm^2 sec at 10^5 km from the white dwarf. The direct absorption of X-rays will be due to the heavy element constituents, with oxygen and neon the principal contributors. The cross section for their absorption depends on the abundances, but using solar abundances we find about 6 cm^2/gm for 3 keV X-rays. Due to the outward decrease in temperature the Ca II lines will naturally be formed at a greater distance from the center of the cloud than will the Balmer lines, thus explaining their relative sharpness since the mass motions will be smaller at this distance.

Three previously unexplained observational facts are natural consequences of the present model. The large scatter in the Balmer line radial velocities is expected from slight asymmetries in the gas streaming. These asymmetries need not be very great because the mass motions are of the order of 1000 km/sec while the binary orbital velocities are of the order of 200 km/sec. The reason for the weakness of the first two Balmer lines is clear when we realize that they are not formed on a stellar component and filled in by a bremsstrahlung spectrum, but are formed in the plasma cloud surrounding the white dwarf and filled in by light from the G-star. Since the G-star continuum becomes stronger relative to the cloud continuum toward longer wavelengths, the low number Balmer lines will be those most weakened. The minute-to-minute fluctuations in optical brightness are expected because the time scale for significant changes in the system is very short. It should take only about twenty minutes for material to fall all the way from the L_1 point to the cloud, so rapid brightness changes should definitely occur.

At the beginning we said that this model for Cyg X-2 would be found similar to systems recognized earlier from different observational evidence. These are certain old novae*, specifically the close binaries WZ Sge and DQ Her. For WZ Sge, which is actually a recurrent nova, Krzeminski and Kraft [13] have directly observed the lines of a white dwarf component, and for DQ Her one is indicated by the color and luminosity. WZ Sge shows gas streaming from the L_1 point toward the white dwarf, but it is not an X-ray source at presently detectable flux levels. In general, old novae which can be studied in detail spectroscopically often consist of a 'blue' primary component, which can sometimes be shown to be a white dwarf, and a 'red' secondary, of middle or late type [14]. Notice that the corresponding features of Cyg X-2 and the old novae have been established from entirely different evidence. In Cyg X-2 we must have a white dwarf because accretion onto a compact object is the only known X-ray generating mechanism sufficiently efficient to yield several tens of solar luminosities, while in WZ Sge we actually see the spectral lines of a white dwarf component. In Cyg X-2 we must have transfer of material from the secondary to the primary components because it is required by the accretion mechanism and by the Balmer line profiles, while in WZ Sge the phase dependence of the radial velocities shows that we are seeing matter flowing from the secondary component toward the white dwarf.

It seems highly probable that Cyg X-2 is a nova in some stage of development and, if we compare it to WZ Sge, we should probably favor a pre-nova interpretation. In WZ Sge the secondary component is spectroscopically invisible and has a mass, according to Krzeminski and Kraft, of only 0.03 $m_\odot$. If this is the actual mass of the object, it is somewhat argumentative whether it should be called a star. We seem to be viewing the remains of a star left over after a long interval of mass transfer. In Cyg X-2, however, most of the visible light comes from the secondary component, indicating that it still has a respectable mass. The identification of Cyg X-2 as a (probably pre-) nova is strengthened when we recall that its radial velocities indicate kinematics similar to those of old novae [4].

Cyg X-2 is an interesting object even when considered by itself, but it now appears much more so in view of its remarkable similarity to known post-novae. Further observations might solve one of the long standing problems of astrophysics, the search for the mechanism of the nova phenomenon.

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