THE BLUE STRAGGLER F190: A CASE FOR MASS TRANSFER

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ABSTRACT. The blue straggler F190 is a member of the old open cluster M67. We argue that F190 may still be in the final stages of the mass transfer that has made it into a blue straggler. We use the turnoff mass of the cluster and the mass function derived from the spectroscopic orbit for F190 to constrain the masses of each member of the binary, both before mass transfer and now. We find that the mass transfer must have been nearly 100 percent efficient.

1. MEMBERSHIP IN M67

The old open cluster M67 is one of the first stellar systems where blue stragglers could be identified (Johnson & Sandage 1955, Eggen & Sandage 1964). For 9 of our 13 blue stragglers in M67, we are able to measure radial velocities with the CfA digital speedometers. Although 5 of these blue stragglers show definite velocity variations in our data, F190 (Fagerholm 1906) is the only one with a short period (Milone *et al.* 1992). This makes F190 especially interesting as a possible candidate for a history of mass transfer, one of the classical mechanisms proposed as a way to manufacture blue stragglers in an old stellar population (McCrea 1964).

There can be no doubt that F190 is a member of M67. The 1950 position (08:48:50.18 +12:02:28.3, Girard *et al.* 1989) places it 3 arc min from the center of the cluster, which has a half-mass radius for the single stars of about 10 arc min (Mathieu & Latham 1986). In addition, the proper motion of the star matches the cluster motion very closely, with a 99 percent probability of membership on this basis (Girard *et al.* 1989). Finally, the γ velocity of the spectroscopic orbit is 34.42 ± 0.48 km s^{-1}, which matches the cluster velocity of 33.6 km s^{-1} within the errors and cluster velocity dispersion of 0.5 km s^{-1} (Milone & Latham 1992).

2. PHOTOMETRY AND PRIMARY MASS

The apparent magnitude and color of F190 (V = 10.95, B-V = 0.22, U-B = 0.29, V-R = 0.10; Gilliland *et al.* 1991) place it well to the blue of the Main Sequence Turnoff and somewhat off the Zero Age Main Sequence (ZAMS) for the cluster. If we assume that there is no light coming from the companion, then we derive a mass of 2.0 $M_\odot$ and an age of 1.0 Gyr for the somewhat evolved single star that would match

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the position of F190 in the color-magnitude diagram, using the evolutionary models calculated by VandenBerg (1985). On the other hand, if we assume that the primary of F190 is on the ZAMS with $V = 11.25$ and $B\text{-}V = 0.09$, then we derive a mass of 2.2 $M_\odot$. In this case the apparent magnitude and color of the secondary would be $V \sim 12.7$ and $B\text{-}V \sim 0.6$, corresponding to some sort of subgiant. These two extreme assumptions about the evolutionary position of the primary and the amount of light contributed by the secondary limit the mass of the primary to the range of 2.0 to 2.2 $M_\odot$. Of course, these mass estimates may be in error if the structure of the primary has been changed by mass transfer and the star has not adjusted itself to the same configuration as a single star of the same mass.

3. ORBIT AND SECONDARY MASS

Although F190 had long been suspected of being a spectroscopic binary with a period of about 4 days (Deutsch 1968), it is only recently that an orbit has been solved and published (Milone *et al.* 1991). A plot of the orbital solution, using all of the CfA velocities measured up to mid 1991, is show in figure 1. The velocities were derived by cross-correlation against a synthetic spectrum calculated from a Kurucz model atmosphere with an effective temperature of 7500 K, a log gravity of 4.0, a solar metallicity, and a projected equatorial rotation of 80 km s^{-1}. The elements for this orbital solution are listed in table 1. If we plug the mass limits for the primary found in the previous section into the mass function derived from the orbital solution, $f(M) = (M_2 \sin i)^3/(M_1 + M_2)^2 = 0.0015$, we get $M_2 \sin i = 0.21$ and 0.19 $M_\odot$ for the secondary, for primary masses of $M_1 = 2.2$ and 2.0 $M_\odot$, respectively.

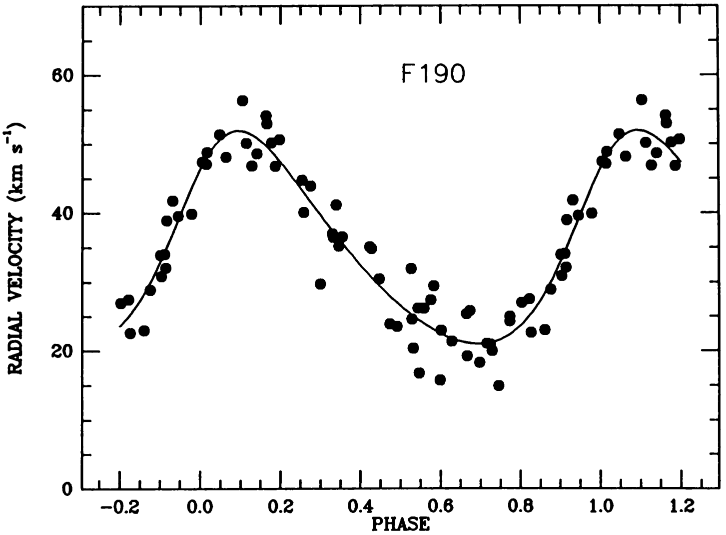

Figure 1. The observed velocities and the velocity curve for the orbital solution for F190.

Table 1. Elements of the orbital solution for F190

$\gamma = 34.42 \pm 0.48$ (km s^{-1})	$K = 15.48 \pm 0.71$ (km s^{-1})
$e = 0.205 \pm 0.043$	$\omega = 310 \pm 9$ (°)
$T = 2445000.02 \pm 0.14$ (JD)	$P = 4.18284 \pm 0.00015$ (d)
$f(M) = 0.0015 \pm 0.0002$ ($M_\odot$)	$a_1 \sin i = 0.872 \pm 0.041$ (10^6 km)
$N_{obs} = 62$	*rms* velocity residuals = 3.7 km s^{-1}

4. MASS TRANSFER?

Has F190 been turned into a blue straggler by recent mass transfer? In this section we explore a scenario in which F190 was originally a close binary composed of two main-sequence stars (Collier & Jenkins 1984). The more massive component evolved first, expanded until it filled its Roche lobe, and then transferred mass onto its companion very quickly until the masses were equal. During this phase of mass transfer the orbital separation and period both became smaller. Subsequently, the mass transfer went much more slowly, because the orbital separation grew larger as the mass-donating star became progressively less massive than the mass-receiving star, and further evolution of the donating star was required to sustain the mass transfer.

If the original primary (now the secondary) of F190 was formed at the same time as all the other stars in M67, then when it started evolving to a giant, it must have been at the Main Sequence Turnoff. By a similar argument the original secondary (now the primary) must have been less massive than the turnoff mass at that time. How long ago did the original primary start to evolve, and what was the mass at the Main Sequence Turnoff then? The answers to these questions need to be worked out. To keep the argument simple, we will suppose that mass transfer began fairly recently, and that the turnoff mass was only slightly larger than the value now, which is 1.26 $M_\odot$ (VandenBerg 1985). In this case the original total mass of both stars could not exceed about 2.5 $M_\odot$. This does not leave very much leeway for mass to be lost from the system, because the total mass now must be at least 2.2 or 2.4 $M_\odot$, depending on which of the two limiting masses for the primary we choose, 2.0 or 2.2 $M_\odot$.

Thus the basic conclusion of this chain of argument is that the mass transfer has been quite efficient, and very little mass has been lost from the system. Even for mass transfer that was 100 percent efficient, the orbit can not be more nearly face-on than an inclination of about 45°, or the total mass now would exceed 2.5 $M_\odot$.

There is evidence suggesting that a final slow stage of mass transfer is still underway. The axial rotation of the present primary should be pseudosynchronized with the orbital motion (Hut 1981), but it is not. The angular velocity of the secondary in its orbit at periastron corresponds to a period of 2.1 days, while the rotational period of the primary can not be longer than about 1.2 days, even if the axial rotation is viewed edge on. To calculate this upper limit to the rotational period, we combined the observed projected equatorial velocity $v\sin i$ = 80 km s^{-1} (deduced from the broadening of the spectral lines) with the radius of the star, about 2 $R_\odot$, estimated from the empirical calibration of Harmanec (1988). We argue that the rapid rotation of the primary has been sustained by the final stages of mass transfer, which converts orbital angular momentum into spin angular momentum.

If the system is still in the final stages of mass transfer, then we might expect the primary to be near the ZAMS and for the secondary to be some sort of swollen subgiant which contributes a significant amount of light, especially as one moves towards longer wavelengths. Perhaps the secondary is the source of the infrared excess observed by Peterson *et al.* (1984), although additional observations are needed to distinguish this possibility from an accretion disk. A dramatic confirmation of this picture would be the demonstration that the spectrum of F190 has a second component with an orbital motion of about 150 km s^{-1}.

5. ORBITAL ECCENTRICITY

The orbital eccentricity for F190 is a puzzle. When F190 first started its mass transfer, its orbital period must have been very short, and therefore the orbit must have been circularized by tidal effects (*e.g.* see Latham *et al.* 1992). For example, if no mass has been lost from the system, then the initial period would have been no longer than about a day (Pringle 1988). Such an orbit would be close to contact and would circularize very quickly. If the initial eccentricity is small, then mass transfer tends to circularize the orbit (Paczyński 1971), and we would thus expect F190 to have a circular orbit now. Perhaps the eccentricity that we derive is an artifact caused by the some sort of line asymmetries, similar to the ones that can lead to fictitious eccentricities in the orbital solutions for Algols (Popper 1989). Another possibility is that an accretion disk formed during the mass transfer. It has been shown recently that resonant phenomena in accretion disks can increase the orbital eccentricity of a binary (Artymowicz *et al.* 1991). Yet a third possibility is that a distant third star in a wide orbit has pumped up some eccentricity. Simulations of such a configuration for F190 suggest that an eccentricity of 0.2 can be produced, but only under rather special conditions (Mazeh & Krimolowski, private communication).

6. CONCLUSIONS

We have argued that the blue straggler F190 in the old open cluster M67 has been produced by recent mass transfer, and that the system is still in the final stages of mass transfer now. Several aspects of this picture need to be confirmed. Can a detailed model of the history of the mass transfer give the appropriate time scales? Can it be demonstrated that the present secondary is filling its Roche lobe and is contributing the appropriate amounts of light? Can the spectrum of the secondary be detected and an orbit derived? Should there be an accretion disk now, and should it be detectable? Can a convincing explanation be found for the origin of the orbital eccentricity? These questions should be fun to work on.

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