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ON THE DISTANCE TO CYGNUS X-1 (HDE 226868)*

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ABSTRACT

From *U, B, V* photometry of 104 stars in a field of radius $\sim 30'$ centered on the X-ray binary star Cyg X-1 (HDE 226868), we have studied the color excess $E(B-V)$ as a function of distance. Spectral types were observed *de novo* for 42 of these stars. We conclude that HDE 226868 cannot be nearer than 1 kpc, and is probably at a distance of 2.5 kpc or more. The primary component is therefore a luminous OB star of mass $\sim 30\,\mathfrak{M}_\odot$, and the X-ray component has a minimum mass $\sim 6\,\mathfrak{M}_\odot$.

Subject headings: binaries — black holes — X-ray sources

Since HDE 226868, the optical object identified with Cyg X-1, is a single-lined spectroscopic binary, the minimum mass of the unseen X-ray component (obtained for the orbital inclination $i = 90°$) depends on the mass assigned to the optical primary. If one assumes that the source of X-ray power is to be associated with a collapsed object, one finds that the mass of the collapsed object is greater than $\sim 3\,\mathfrak{M}_\odot$, and therefore is a "black hole" (Ruderman 1972), if the mass of its OB-star companion is greater than $\sim 9\,\mathfrak{M}_\odot$ (cf. Bolton 1972). At first glance, one would seem to have no difficulty in assigning to the primary, of spectral type O9.7 Iab (Walborn 1973), a mass well in excess of $9\,\mathfrak{M}_\odot$.

However, as pointed out by Trimble, Rose, and Weber (1973) and independently by Blumenthal, Faulkner, and Kraft (1973), the assignment of an MK type leads only to a statement about a star's surface gravity and temperature and does not directly give the mass unless the state of evolution is known. Thus if we take a mass $>9\,\mathfrak{M}_\odot$ for the primary, we are assuming it is a post–main-sequence star with shell hydrogen burning; it could as well be a star of much lower mass ($\sim 1\,\mathfrak{M}_\odot$) in a later evolutionary stage with a thin hydrogen envelope and shell helium burning (cf. Paczyński 1970; Rose and Smith 1970). Similar low-mass models with inert helium cores and hydrogen-burning shell sources have been calculated by Trimble (1973). The lifetimes of these various models range from 1 to only about 100 times shorter than the lifetimes expected for a massive hydrogen shell burner (cf. Ziołkowski 1972), and thus low-mass primaries for Cyg X-1 cannot be ruled out of consideration simply on statistical grounds. Assignment of $1\,\mathfrak{M}_\odot$ to the primary, for example, leads to a minimum mass for the X-ray component of about $0.9\,\mathfrak{M}_\odot$, and for $i \geqslant 36°$ the mass of the X-ray component will be less than $2\,\mathfrak{M}_\odot$, and therefore comfortably accommodated by present models of neutron stars.

The two kinds of models differ sharply in luminosity; for the case of the massive primary, the distance to Cyg X-1 is about 2 kpc or greater (Bolton 1972) whereas for the low-mass case the distance will be somewhere in the range 200–900 pc. It is therefore important to establish from model-independent considerations which of these two distance ranges is correct; previous attempts based on probable association mem-

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bership (Bolton 1972) or strengths of interstellar lines (Smith, Margon, and Conti 1973) have not been very definitive, mainly because of the paucity of available observational material.

We report here an attempt to establish a scale of interstellar reddening as a function of distance from photometry of stars mostly within a radius of 30′ of HDE 226868. U, B, V observations of 104 stars were made with the 24-inch (61-cm) Lick reflector on the nights of 1973 July 4–7 and July 31 (UT). Details of the observations are available from the Lick Observatory. With $V = 8.87$, $(B-V) = 0.81$, and $(U-B) = -0.30$, HDE 226868 is the apparently brightest, and probably one of the intrinsically brightest, stars in the field even if the low-mass case were the correct one. We therefore measured colors and magnitudes for stars as faint as $V = 13$, hoping to find at least a few stars as distant as or more distant than the X-ray source.

The conventional color-color plot is shown in figure 1. For a reddening trajectory $E(U-B)/E(B-V) = 0.72 + 0.05\ E(B-V)$, we find a very large color excess $E(B-V) = 1.12$ mag for HDE 226868. We therefore suspected that a few of the apparently unreddened F-type stars in figure 1 are actually highly reddened B-type stars. To check on this possibility, we obtained spectral types for 42 stars with the new image-tube scanner (Robinson and Wampler 1972) operated at the Cassegrain focus of the 120-inch (3-m) telescope. The main sequence of the Coma cluster was also observed with the scanner and was used as a set of standard spectra of the MK system (Mendoza 1963). These were supplemented with objective prism spectral types from the HDE and the surveys by Numerova (1958) and Annear (1953).

Stellar distances were obtained in the usual way using Blaauw's (1963) calibration of the absolute magnitudes and a ratio $A_V/E(B-V) = 3.0$. The resulting plot of color excess $E(B-V)$ as a function of distance is shown in figure 2. Only stars with $E(B-V) \geqslant 0.05$ were plotted. Two stars were judged from scans to be more luminous than class V, but we were unable to distinguish between assignment of class III or IV; horizontal lines in figure 2 establish the corresponding range of uncertainty in distance. Few stars were found with distances in excess of 1200 pc; however, at 900 pc, the upper limit for low-mass models of HDE 226868, the mean color excess is only 0.35 mag. We conclude that HDE 226868 is not closer than 1 kpc, and that its minimum distance is about 2.5 kpc. The actual distance probably cannot be established

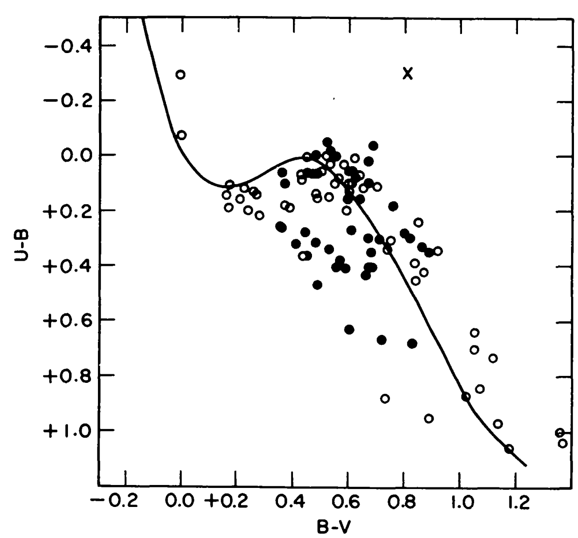

FIG. 1.—$(U-B)$ versus $(B-V)$ plot for stars in the vicinity of HDE 226868. Filled circles correspond to stars for which spectral types were estimated from ITS scans. The cross refers to HDE 226868.

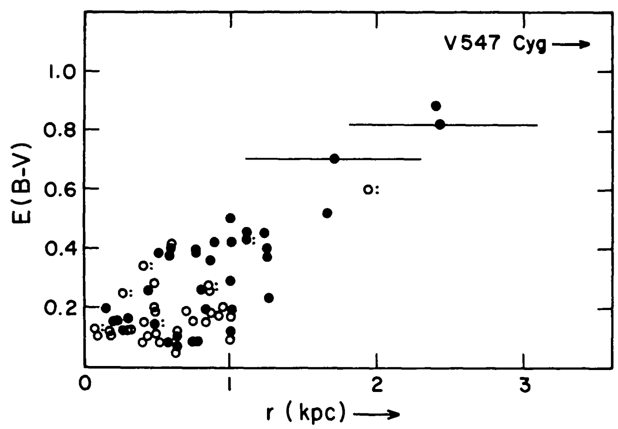

FIG. 2.—Color excess $E(B-V)$ as a function of distance for stars in the vicinity of HDE 226868. Filled circles correspond to stars for which spectral types were estimated from ITS scans; colons indicate uncertainty and stars with $E(B-V) < 0.05$ have been omitted. The location of the cepheid V547 Cyg at $E(B-V) = 1.1$ and $r = 6.6$ kpc is indicated by the arrow. Horizontal lines indicate the uncertainty in distance for two stars of luminosity class III or IV. The color excess for HDE 226868 is $E(B-V) = 1.12$.

directly from the plot: the cepheid variable V547 Cyg which lies in the field at a distance of 6.6 kpc (Fernie and Hube 1968), has $E(B-V) = 1.1$, essentially the same as HDE 226868. It thus appears that the line of sight "breaks through" the dust layer at a distance of about 3 kpc, corresponding to a distance above the galactic plane of 150 pc; figure 2 can obviously give us no information on distance beyond that point.

Interpreted as a massive hydrogen shell-burning star, the primary has $\mathfrak{M} \sim 30\mathfrak{M}_\odot$ (Ziołkowski 1972), and the minimum mass ($\sin i = 1$) of the X-ray component is therefore near $\mathfrak{M} \sim 6\mathfrak{M}_\odot$. This result could be avoided only if we are willing to postulate that most of the reddening of HDE 226868 results from circumstellar matter in the immediate vicinity of the X-ray source. As pointed out in the companion *Letter* (Margon, Bowyer, and Stone 1973), this is unlikely since the ratio of linear polarization to reddening for HDE 226868 is similar to that for OB stars in the same part of the sky.

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