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ON THE NATURE OF THE DWARF CARBON STAR G77-61[1]

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ABSTRACT

A variety of new astrometric, photometric, and spectrophotometric data are presented for the low-luminosity carbon star G77-61. The improved parallax yields $M_v = +10.08 \pm 0.43$, while the revised temperature estimate from infrared, optical, and ultraviolet fluxes is 4100 (+200, −300) K, yielding $\log L/L_\odot = -1.75 \pm 0.16$. Most importantly, radial velocity variations have been detected, with the binary period 245 days. The unseen companion probably is a cool white dwarf of much higher mass than the visible object. The absorption spectrum lacks detectable metallic hydride bands and shows only very weak metallic lines. Both the spectrum and the H-R diagram position below the main sequence require G77-61 to be either extremely metal poor, or helium enriched and at least moderately metal poor. The two possibilities carry different implications for the evolutionary history of the object.

The most straightforward evolutionary hypothesis is that G77-61 has an extremely metal poor composition and that it accreted a small amount of carbon-rich material when the now unseen primary was at maximum radius. This could have inverted the C/O abundance of the secondary without achieving common envelope evolution and a shorter period. Should the chemical composition prove to be helium enriched, however, then substantial mass transfer must have occurred from a helium-rich (R CrB–like?) object. It is difficult to see how such an object would have avoided spin-down to a shorter period orbit.

Subject headings: stars: abundances — stars: binaries — stars: carbon — stars: individual

I. BACKGROUND

G77-61 is the only cool star near the main sequence that is known to have strong carbon features (Dahn *et al.* 1977, hereafter Paper I). That it lies near the main sequence at $M_v \approx +10$ is clearly established by both the accurate trigonometric parallax and the space motion constraint imposed by its proper motion. It has to be fainter than $M_v \approx +8$ to be bound to the Galaxy, yet it cannot be a degenerate star, since that would require the true $\pi_{\rm trig}$ to be $>0''.1$, with the measured value a vast underestimate.

The strong carbon (C_2, CN, CH) bands are the principal feature which distinguishes G77-61 from an M dwarf. We wish to address the question of the origin of this carbon. In Paper I, the hypothesis that this pollution could be due to binary evolution was discussed. A main-sequence star cannot be sufficiently evolved to produce carbon, but the carbon could have been produced by a more massive primary and transferred to the secondary. The massive component might now be an invisible remnant.

An alternate explanation of the carbon enhancement is primordial inhomogeneities. Carbon *et al.* (1982) have suggested a scenario allowing many of the main-sequence dwarfs in metal-poor globular clusters to be spectroscopic carbon stars; that is, they might have abundances of C > O. If G77-61 were such a star, it would be an observational keystone for understanding part of the early chemical history of the Galaxy. Indeed, its space motion clearly labels it as a member of the halo population.

In this paper we have brought together several individual studies to try to understand the nature and origin of this star. Section II presents improved astrometry and new radial velocity measurements which establish that G77-61 is a binary star. Section III details infrared and spectrophotometric observations, as well as the results of some spectrum synthesis calculations. Section IV considers the possible evolutionary histories for the object and presents some stellar structure constraints. In § V we offer what conclusions can be reached at this time.

II. OBSERVED MOTIONS OF G77-61

a) New Astrometry and Astrometric Constraints

Following the completion of Paper I, G77-61 was reinserted on the US Naval Observatory parallax program in order to improve the parallax and to search for the perturbations of a (hypothetical) companion. The plate material to date consists of the 25 plates from 1965.70 to 1971.10, plus 46 plates from 1977.72 to 1981.07. The solution for both plate sets together yields the following revised values:

$$\pi_{\rm rel} = 0''.0150 \pm 0''.0022 \text{ (mean error)}$$

$$\pi_{\rm abs} = 0''.0173 \pm 0''.0034 ,$$

corresponding to $M_v = +10.08 \pm 0.43$.

[1] Research reported here used the Multiple Mirror Telescope (MMT) Observatory, a facility operated jointly by the University of Arizona and the Smithsonian Institution.

[2] Guest Investigators on the *International Ultraviolet Explorer* satellite, operated by NASA at the Goddard Space Flight Center, Greenbelt, Maryland.

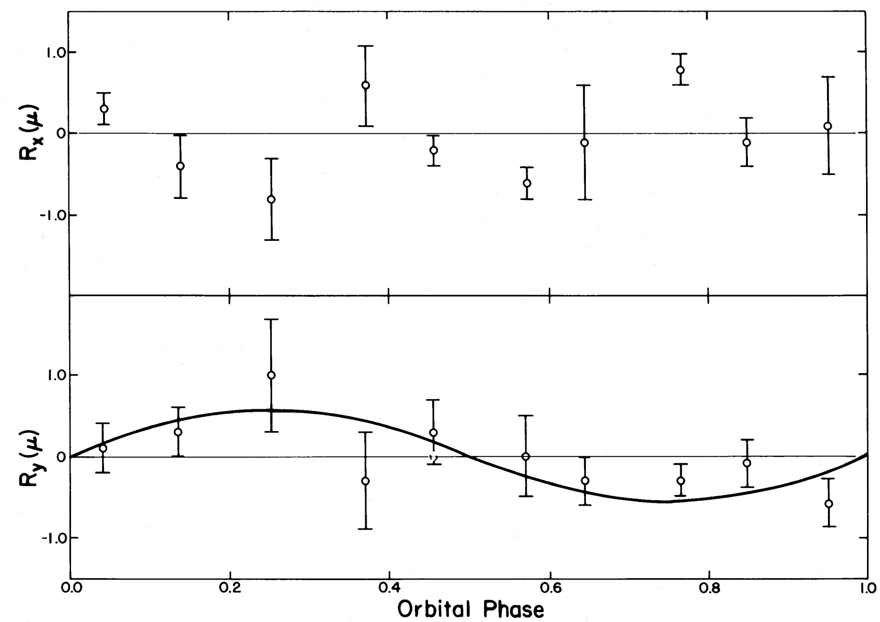

FIG. 1.—Normal residuals of G77-61 in the x and y positions phased to 245.5 days. A predicted sinusoidal perturbation curve corresponding to an amplitude of 0.44 a.u. (0.55 μm) is arbitrarily shown only with y residuals. A reduction of the parallax within the stated uncertainty to 0".014 would reduce the amplitude to 0.45 μm; this would decrease absolute magnitude, placing the star in the upper end of the box shown in Fig. 7. Amplitude of the y residual could also be reduced by placing some of the amplitude in the x residual.

This makes the star ~0.4 mag fainter (and farther from the main sequence) than the original value (Paper I). The proper motion was found to be 0".7725 yr^{-1} with a position angle of 165°.8. At the distance required by the parallax, this implies a tangential velocity of 244 km s^{-1}. Combined with this information and the V magnitude of 13.89 (Paper I), the mean radial velocity (γ) found in § IIb implies a total space motion in galactic coordinates of $(U, V, W) = (-93, -183, -44)$ km s^{-1}, consistent with its being a Population II object.

The mean error of unit weight for this plate series was 1.06 μm; this is smaller than average (~1.09 μm), indicating an excellent solution. However, experience with other USNO plate series indicates that perturbations with a full amplitude of ~1 μm would be easily seen, but smaller perturbations can be completely hidden by the random noise and, hence, not produce a larger than average mean error of unit weight.

In Figure 1, the normal residuals of the G77-61 positions are plotted against the 245.5 day orbital presented in § IIb). Displayed with the y residuals is the expected total perturbation curve for the orbit derived in § IIb, assuming an eccentricity $e = 0$, a mass of the unseen primary star of 0.6 $M_\odot$, and a mass of the visible (carbon-rich) secondary of 0.3 $M_\odot$. While the period and phasing of the expected perturbation are predicted from the radial velocity solution, the orientation of the orbit on the plane of the sky is unknown, so that the fractions of the amplitudes expected in x or y residuals are unknown. The plotted residuals do not appear inconsistent with the predicted perturbation which has a total amplitude of ~0.5 μm.

b) *Radial Velocity Measurements*

Thirteen radial velocity measurements were obtained of G77-61 over the period 1982 September–1985 Feburary. The results are summarized in Table 1. The observations were made with the MMT and echelle spectrograph and were reduced using the Smithsonian Astrophysical Observatory cross-correlation software (Tonry and Davis 1979).

For most of these measurements the spectrograph was centered on the λ5636 band head of the C_2 Swan system. The advantages of this spectral feature for radial velocity purposes over other possible carbon star absorption bands have been discussed by Aaronson (1983). Some of the velocities listed in Table 1 were determined using a region near the λ5165 band head instead, and the larger adopted error reflects this fact. All of the measurements have been tied together through observations of twilight sky, and the quoted uncertainties are believed to reflect the external as well as internal errors. In addition to twilight, templates were selected from a list of (nonvariable) galactic R and CH stars being monitored by McClure (1982).

It is clear from Table 1 that G77-61 exhibits significant radial velocity variations. We can rule out atmospheric

TABLE 1

G77-61 RADIAL VELOCITY OBSERVATIONS

JD 2,445,000+	V (km s^{-1})
252.0	−17 ± 1
271.9	−24 ± 1
310.7	−40 ± 1
402.6[a]	−44 ± 3
718.7	−14 ± 1
734.7	−14 ± 1
735.7	−14 ± 1
974.9	−16 ± 1
1015.7	−24 ± 1
1016.9[a]	−26 ± 1.5
1018.8[a]	−28 ± 1.5
1019.8[a]	−27.5 ± 1.5
1121.7	−46 ± 1

[a] Determined from the λ5180 setting.

motions as a cause of these variations, since the stars being studied by McClure (1982) appear to exhibit such motions only at the <2 km s^{-1} level. Rather, the conclusion that G77-61 is a member of a binary system seems inescapable.

From its position on the H-R diagram, we suppose the mass of the observable component to be $\sim 0.3\ M_{\odot}$. Orbits with periods short enough to agree with the limits placed by astrometry would quickly become circular because of tidal interaction and, finally, mass exchange. Thus, we use Kepler's laws with the assumption of a circular orbit to fit the velocity which is given by

$$V_{\rm radial} = K \sin i \sin [2\pi/P(T - T_0)] + \gamma ,$$

where

$$K \sin i = \text{apparent orbital velocity}$$

$$= \frac{2\pi M_1 \sin i}{(M_1 + M_2)^{2/3} P^{1/3}} = 18.94 ,$$

where γ is the systemic velocity ($= -33.6$ km s^{-1}), T_0 is the epoch ($= 2445173.8$ HJD), P is the period ($= 245.5$ days), σ are the velocity errors from this solution ($= 1.07$ km s^{-1}).

These points are found to conform well to the assumed circular orbit (Fig. 2), and a least-squares fit has as its only acceptable solution that listed above. The mass function requires the invisible component to have a mass greater than $0.55\ M_{\odot}$ (assuming the mass of the observed component to be $0.35\ M_{\odot}$). This is consistent with a mass required of a white dwarf remnant.

We did test the fit of the velocity points to eccentric orbits and found them inconsistent with an eccentricity of $e > 0.2$. Again, the best fit was obtained for a circular orbit.

III. ENERGY DISTRIBUTION AND SPECTRUM

a) Infrared Photometry

JHK photometry of G77-61 was obtained (1) with the Harvard-Smithsonian InSb detector system on the Kitt Peak 2.1 m telescope in 1980 October and (2) with the CTIO 4 m reflector in 1984 February. Reduction to the standard system of Frogel *et al.* (1978) yielded $K = 10.47$, $J-H = 0.70$, and $H-K = 0.37$ for the first measurement, in good agreement with the CTIO values of $K = 10.49$, $J-H = 0.64$, $H-K = 0.36$. The visual magnitude of $V = 13.90$ gives $V-K = 3.42$, which corresponds to an effective temperature of 4000 K according to the calibration of Mould and Hyland (1976). This is consistent with the estimate of 4100 K from Paper I.

To determine the bolometric correction, we have integrated the energy distribution given in Figure 3. An L magnitude of 10.15 was assumed, based on the blackbody fit. We obtained BC $= -0.96$. However, the bolometric correction of a 4100 K blackbody is somewhat less (~ -0.6). This difference (0.36 mag) can be attributed to blanketing in the V filter (Smak and Wing 1979). We shall adopt the value -0.96 in § IV. In either case, the star lies distinctly below and to the left of the Population I main sequence, in the region of the extreme subdwarfs having low metallicity.

That the infrared blanketing may be different for G77-61 than for M dwarfs and subdwarfs is indicated by its position in the *JHK* two-color diagram (Fig. 3). For comparison we also show the locus of field K and M giants and the carbon stars recently observed in the Magellanic Clouds (Aaronson and Mould 1982; Cohen *et al.* 1981). The hatched region is occupied by M dwarfs (Mould and Hyland 1976; Persson, Aaronson, and Frogel 1977). G77-61 is seen to lie at the cool end of this region, close to stars, having $T_{\rm eff} < 3000$ K and $M_v > +16$, such as Wolf 359 and Proxima Centauri. Subdwarf M stars are located at the bottom of this hatched region, somewhat opposite the position of G77-61. Note, in particular, that G77-61 is located in the *JHK* diagram among the metal-poor carbon giants of the Carina dwarf spheroidal galaxy (Mould *et al.* 1982).

It is unreasonable to interpret G77-61 from the *JHK* colors alone as a star at the low-luminosity end of the main sequence. Given the M_v value (§ II), this would require G77-61 to be a composite spectrum, with a blue carbon star dominating the visual light and a very late M star dominating the *JHK* colors. This is inconsistent with the fact that both the optical/near-infrared (Paper I) energy distribution and the $V-K$ color give essentially the same color temperature. It is more reasonable to suppose that differences in *JHK* blanketing between G77-61 and the oxygen-rich dwarfs and subdwarfs account for its location in Figure 3. We know that the blue $J-H$ colors of M dwarfs are due to the suppression of the H^- opacity peak in

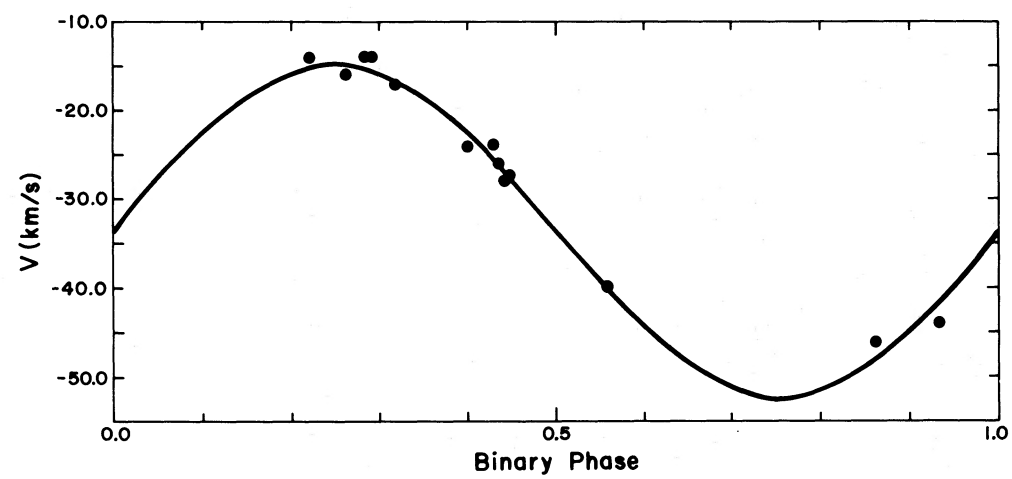

FIG. 2.—Fit of the best circular orbit is shown. While a small amount of eccentricity (<0.2) is possible, an eccentricity larger than this significantly reduce the goodness of the fit.

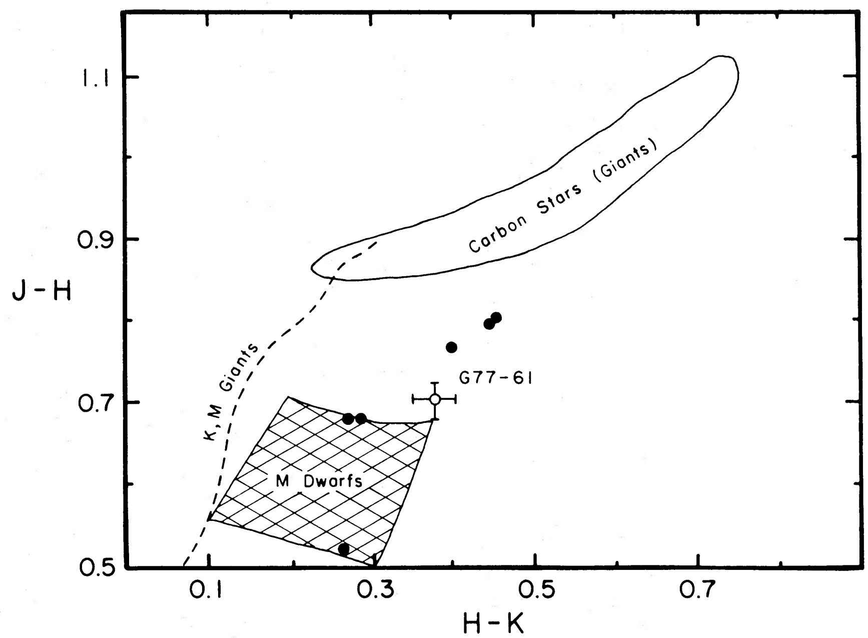

FIG. 3.—Photometric two-color diagram—$J-H$, $H-K$—for G77-61. Shown schematically are the areas in this diagram occupied by oxygen-rich dwarfs, giants, and carbon stars. *JHK* colors of carbon stars from the Carina dwarf spheroidal galaxy are shown as filled circles; these bracket the position G77-61.

the high-gravity atmospheres of these stars (Mould and Hyland 1976). It is difficult to predict the displacement of a carbon dwarf which may be helium enhanced as well as extremely metal poor. Dwarf atmosphere models with C opacity and appropriate abundances would be helpful in investigating this possibility. Infrared spectroscopy would be valuable to check for C_2 and CO features (or, alternatively, for the H_2O signature of a cool companion star).

b) New Optical Spectrophotometry

The data of Paper I are complemented here by three sets of new measurements: (1) multichannel spectrophotometry obtained through a larger entrance aperture and, hence, representing a more accurate absolute energy distribution; (2) red spectrophotometry concentrating on the features found in metal-poor dwarfs at wavelengths redder than those covered in Paper I; and (3) improved, higher resolution optical spectrophotometry covering the Mg I λ5175 and Mg H λ5211 regions. Each of these is discussed in turn.

G77-61 was scanned with the Palomar 5 m reflector and multichannel spectrophotomer (MCSP) on 1977 October 22. The star was accurately measured between 3200 and 10700 Å at 80 Å spectral resolution below 5800 Å and 160 Å longward of this wavelength (see Oke 1974). No channel had a standard deviation larger than 0.2 mag, and most have errors less than 0.1 mag. The red end of the spectrum has the higher accuracy. These fluxes, along with those from the infrared photometry and ultraviolet spectrophotometry (see § III*c*), are plotted in Figure 4. The vertical units are AB magnitudes (m_ν), which can be converted into fluxes (f_ν) per unit frequency interval. Note that the CN features identified here and in the higher resolution red spectrum (discussed next) are considerably weaker than found in carbon giants. This could, of course, merely be the effect of a higher $T_{\rm eff}$ or of the higher gravity which suppresses CN in oxygen-rich dwarfs. If a very red dwarf companion did exist (see § III*a*), its TiO bands would mask the red CN seen in Figure 4.

Spectrophotometry covering the red interval 6700–8700 Å at 4 Å resolution was obtained with the Steward Observatory 2.3 m reflector and intensified analog Reticon system. In Figure 5, this G77-61 spectrum and that of a parallax subdwarf having very similar M_v, viz. G95-59 ($M_v = +11.5$; Dahn and Priser 1973), are displayed. An optical spectrum of the latter has been discussed by Spinrad (1979). G95-59 has three properties characteristic of Population II subdwarf M stars: (1) it lies ~ 1.5 mag below the old disk main sequence in the (M_v, $V-I$) H-R diagram; (2) it has a high space velocity; and (3) it shows the classic sdM spectroscopic features (e.g., Greenstein and Eggen 1966; Ake and Greenstein 1980). These are very strong Mg H and Cz H bands, relatively weak TiO bands, and abnormally strong atomic lines of Na I and Ca I. On this infrared scan we detect K I lines near 7700 Å, just redward of the atmosphere A band, and Na I λ8192.

G77-61 exhibits the first two of the subdwarf properties discussed above. However, its optical-infrared spectrum is totally unlike that of G95-59 and other sdMs. G77-61 shows at best very weak atomic features, such as Na I at 5892 Å (Paper I). There is no evidence in these data for the Ca H band system near 6800 Å, which is normally strong in subdwarfs (e.g., Mould 1976), despite the fact that this feature is much more favorably located than the shorter wavelength hydride bands (5200 Å, 6385 Å) already noted as absent in the Paper I spectra. The latter may be more heavily blanketed (masked) by carbon features.

Given a temperature estimate of $T_{\rm eff} \approx 4100$ ($+200$, -300), we ask whether the lack of hydride bands leads to an interesting limit on the metal abundance of the star. We can estimate the limiting central depth of the strongest of these bands—the Ca H (6830 Å) feature—from the red (Reticon) spectrophotometry in Figure 5. The subdwarf M star G95-59 has a very strong Ca II feature and an absolute magnitude from its trigonometric parallax very similar to that of G77-61. However, in G77-61, no feature deeper than 10% appears in the vicinity of 6830 ± 100 Å, except for the terrestrial B band of O_2, centered at 6870 Å in both stars. The same test can be applied to the MCSP spectrophotometry (Fig. 4); again, no depression is present to a depth greater than 0.1 mag (very nearly 10% depth over a single 160 Å bandpass).

To make the comparison with Mould's (1976) models, we convert the above estimates to $D(6830)$, a measure of the Ca H band strength. The continuum magnitudes estimated from the MCSP are $m_\nu(6540) = 13.15$, $m_\nu(7500) = 12.80$, leading to an interpolated continuum of $m_\nu(6830) = 13.03$, virtually identical with the observed value. From both the MCSP and the red spectrum, we thus estimate that $D(6830) < 0.1$ (conservatively) and utilize Mould's (1976) calibration of $D(6830)$ with $T_{\rm eff}$ (his Table 3). Even at normal metal abundance (metals/hydrogen), the $D(6830)$ predicted by the models rises rapidly from 0.085 at 4250 K to 0.2 at 4000 K, with correspondingly smaller values for smaller assumed metal/hydrogen abundances. Thus, our measured value $D(6830)$ does not place a useful limit on the abundance if the upper end of our $T_{\rm eff}$ range for G77-61 is applicable. A further check of the latter is available by computing Mould's 1 μm index, using the additional MCSP flux point near 10235 Å. Justification for this particular choice of pseudo-continuum points is given in Wing (1967). We compute that $m_\nu(7540) - m_\nu(10{,}235) =$ "1 μm gradient" = 0.34 for G77-61. This suggests $T_{\rm eff} \approx 4200$ K from the Mould atmosphere analysis, consistent with the assumptions and interpretation of $D(6830)$ given above. The above analysis, however, was done for stars assumed to be both oxygen rich and hydrogen rich. In particular, should the atmosphere and continuum opacity of G77-61 be dominated by helium atoms, then the above discussion may be badly in error. Otherwise, we are better served to try an assessment of different metallic features. However, a helium atmosphere, with low-continuum opacity, would suggest even lower overall abundances of heavy elements.

In Figure 6, we show improved optical spectrophotometry obtained with the Steward Observatory 2.3 m reflector and photon-counting Reticon spectrophotometer at 2 Å resolution. Particularly noteworthy redward of the C_2 (0, 0) Swan band are (1) the detection of Mg I λ5172.7 and λ5183.6 lines with equivalent widths of 1.2 Å and 1.6 Å, respectively, and (2) the absence of a Mg H λ5211 band head deeper than ~5% of the local continuum. The atomic magnesium features are, of course, vastly weaker than those occurring in late K and early M dwarfs and subdwarfs.

The absence of Mg H absorption presents an interesting problem. The predicted number density of this molecule would lead to a detectable band at normal high hydrogen abundance, unless the magnesium is extremely deficient, [Mg] ≈ −4 (Gass, Wehrse, and Liebert 1985). Alternatively, the atmosphere could be deficient in hydrogen (i.e., helium rich), in which case the required metal deficiency from hydride bands alone is relaxed; as noted above, the abundance derivable for

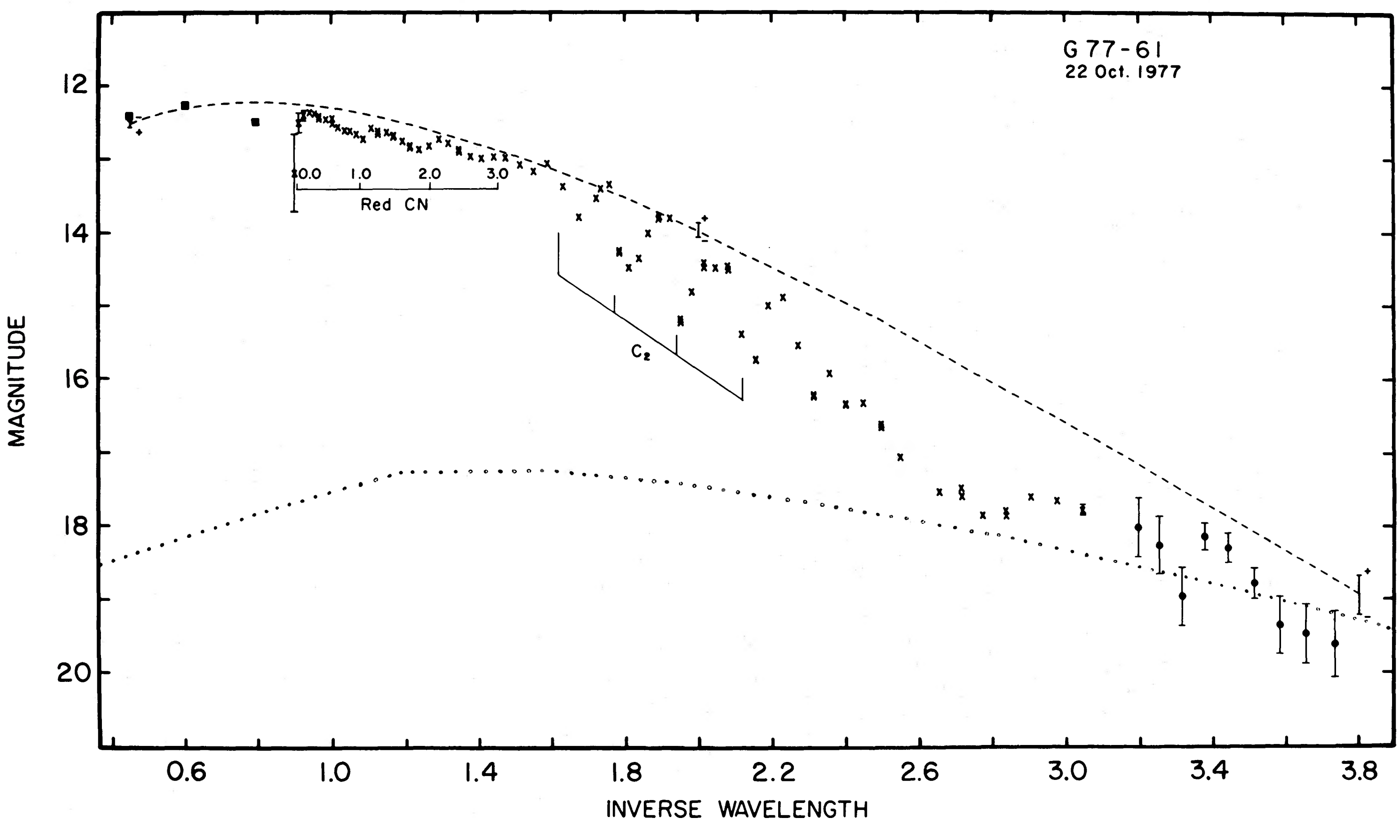

FIG. 4.—Energy distribution from the UV to the IR in magnitudes per unit frequency interval. *IUE* data are shown as filled circles and (large) error bars; Palomar MCSP points are crosses (×), and *JHK* points are filled squares. Dashed curve is a 4000 K blackbody. At extreme right, the vertical bracket shows range through which the end of the blackbody curve would shift for a T_{bb} change of ±100 K. Lower, dotted curve is a white dwarf at 7000 K and 0.012 $R_\odot$ radius; this is probably too bright to be allowed since it would fill in the features found in the carbon dwarf at $1/\lambda > 2.4$.

atomic Mg would be lower. We discuss further the metal deficiency and possible helium richness of G77-61 in § IV*a*.

c) *Ultraviolet Spectrophotometry*

We attempted to detect G77-61 with the long wavelength (LWR) camera on the *International Ultraviolet Explorer* (*IUE*) satellite. The motivation for this observation was twofold. (1) A degenerate companion might be detectable if it were hotter than the visible carbon star. (2) Otherwise, it just might be possible to detect the carbon star's photosphere, providing a further refinement to our temperature estimate and additional information for a future model atmospheres analysis.

An 8 hr exposure was obtained in 1981 November, beginning ~1 hr into the US first shift. Background counts grew to only moderate levels, permitting the exposure to continue ~1 hr into the US second shift when the satellite is near perigee. However, the orientation of the satellite during the long single exposure was such that the solar panels could not adequately provide energy to the satellite. As the telescope became "colder," the telescope focus changed substantially, degrading the spectral resolution and spreading the image over more vertical range of the SEC Vidicon detector. While the detector is linear and no signal was lost, it is clear that the signal-to-noise of the weak detection was degraded. A subsequent, quick spectrum of a much brighter object with the short wavelength (SWP) camera showed that this image was spread over about twice as many vertical pixels as is usual for an untrailed exposure.

The long G77-61 exposure (LWR 11985) is a weak but positive detection. The orthogonalized two-dimensional frame received from NASA was reduced, using a Steward Observatory program for comparison with the standard NASA reduction of the data. The two methods were consistent. The fluxes, with error bars, MCSP, and infrared data, are plotted in Figure 4.

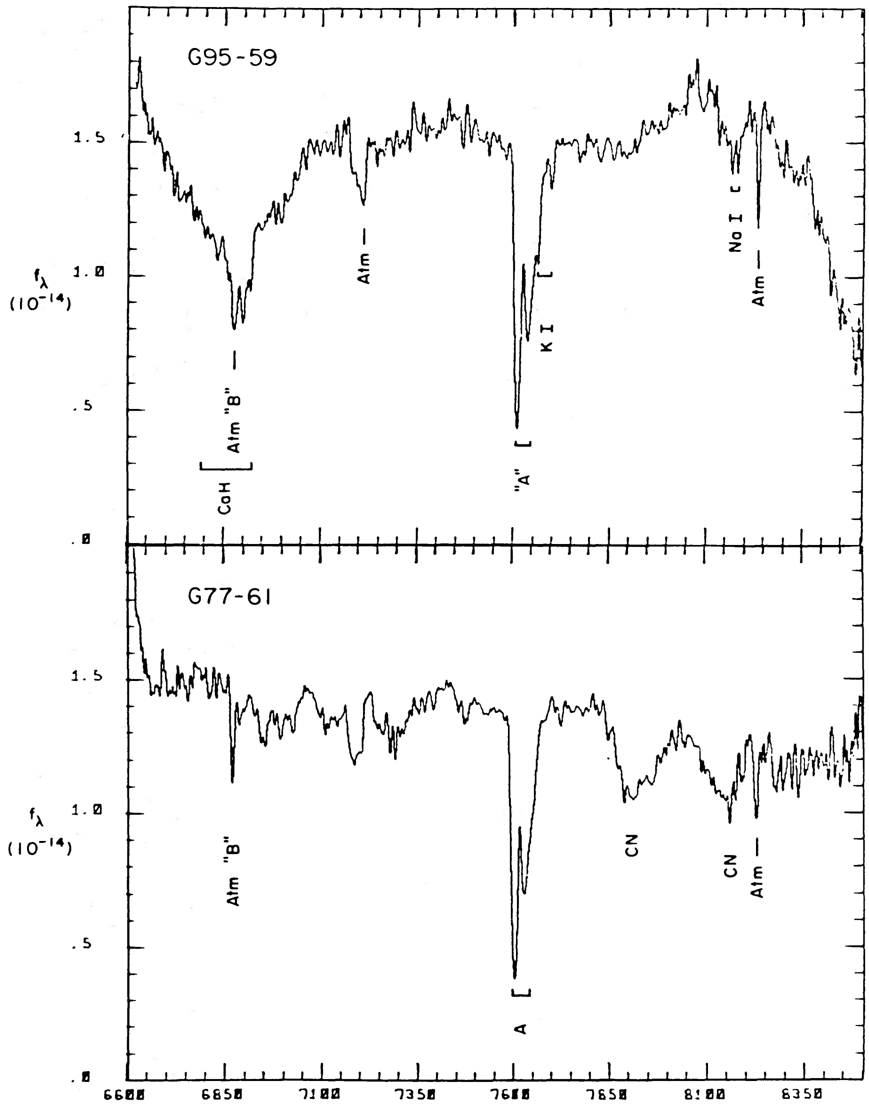

FIG. 5.—Red spectrophotometry of G77-61 and of an oxygen-rich subdwarf M star (G95-59) having very similar parallax M_v. This wavelength range at 4 Å resolution complements the data of Paper I. Important stellar and terrestrial features are marked. Absence of Ca H and other hydride features is in striking contrast to all known late K and early M dwarfs and subdwarfs.

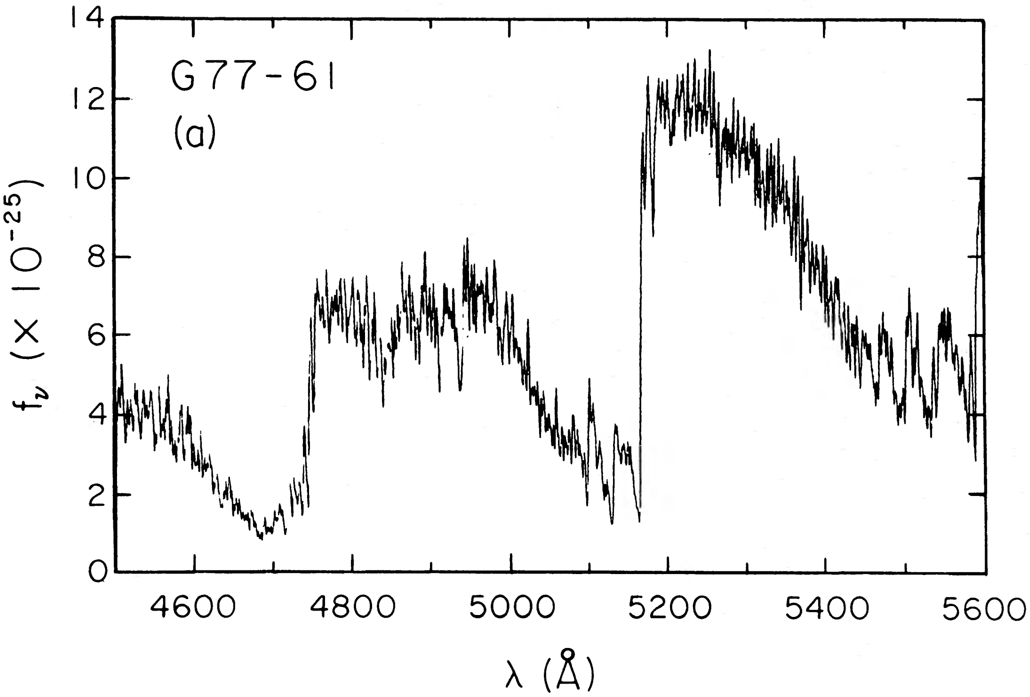

FIG. 6*a*

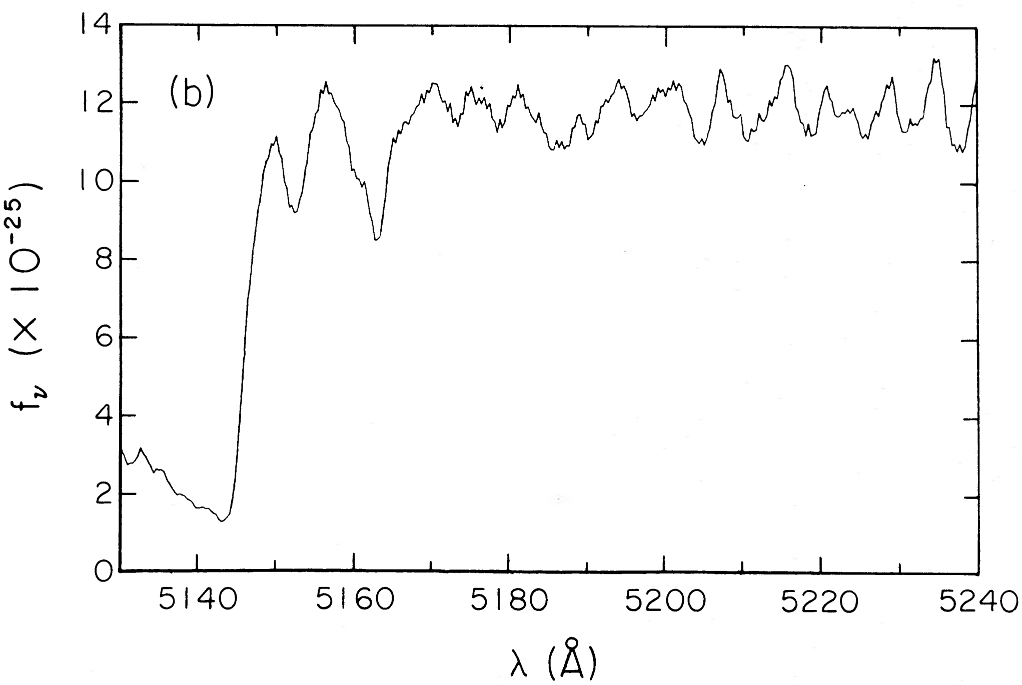

FIG. 6*b*

FIG. 6.—High-resolution (~2 Å) spectrophotometry of G77-61 covering the region 4600–5600 Å: (*a*) whole scan; (*b*) detail of the Mg I, Mg H region near C_2(0, 0) band head. Fluxes are f_ν.

We binned the *IUE* data to the MCSP 80 Å spectral resolution. We also show in Figure 4 a 4000 K blackbody (dashed line) normalized to the G77-61 flux at 1.0 μm.

An inspection of Figure 4 shows the assumed companion of G77-61 to have negligible effect at $1/\lambda > 2.6$. Therefore, if it is a white dwarf, it is cool. The depression below the 4000 K blackbody increases toward higher frequency, as expected in a blanketed star. The *IUE* fluxes fit onto the MCSP flux at $1/\lambda = 3.2$ smoothly and show some downward slope. Two procedures were tried: in Figure 4 we show the expected m_v for a standard white dwarf at 7000 K with 0.012 $R_\odot$ and parallax $0''.017$. A 4000 K blackbody for a white dwarf would be 5 mag below the blackbody fitted for the red star; it is off-scale and clearly would have no effect on the composite energy distribution.

The 7000 K white dwarf, however, lies 4 mag below G77-61, contributing a few percent at $1/\lambda = 1.85$, the V wavelength. If such a white dwarf is subtracted from the composite energy distribution, it would leave the carbon star with negligible flux at $1/\lambda > 2.4$, in contradiction to the appearance of bands in the violet. Therefore, the white dwarf, if present, must have $T < 6000$ K. A 5000 K white dwarf has $\log L < -4$, which is near the lower limit of known red degenerates. It would be $\sim m_v \approx 20$ at $1/\lambda = 2.5$ and 21 at $1/\lambda = 3.0$. A second method was to plot the observed fluxes of red degenerates (Greenstein 1984) of known modulus, shifted to that of G77-61. A few examples include G175-34B (EG 180, 0427+58), $M_V = 13.6$, DC 7, which proves to have excessive flux at $1/\lambda > 2.8$ and a flatter UV slope than the *IUE* observations of G77-61; it resembles the 7000 K blackbody. The heavily blanketed DZ 8 star vMa2 (EG5, WD 0046+05), $M_V = 14.3$, has a very weak ultraviolet continuum and could be tolerated as a companion, although such strong ultraviolet blanketing is rare among cool white dwarfs. Two redder DC 9 degenerates at $M_V = 15.5$ lack *IUE* data, but at MCSP wavelengths are least 4 mag fainter than G77-61; they are LHS 239 (Gr 426, 0747+07) and LHS 1670 (Gr 482, 0423+04). If the companion of G77-61 is a white dwarf, it would have to be among the faintest known degenerates, reasonable if its original mass gave it only short nuclear-burning lifetime, and the remnant has cooled for nearly the age of the Galaxy. Nondetection of its properties may not be as satisfactory as knowing them; yet the fact that it is faint is essential when we consider evolutionary time scales. We explore this question below.

Stars in the halo have generally been considered to have formed about $t(i) = 12$ eons (billions of years) ago; larger $t(i)$, 15–18 eons, are given by VandenBerg (1983), for galactic globular clusters. If we know the cooling lifetime, $t(c)$, of a white dwarf, the nuclear lifetime $t(n)$ of its parent was $t(n) = t(i) - t(c)$. We will assume $t(i) = 12$, for reasons soon obvious. The oldest degenerates known have $t(c)$ of 3–6. Cooling times from Shaviv and Kovetz (1976) for a carbon-oxygen core of 0.8 $M_\odot$ are 3.2 eons at $\log L = -4$, 8 at $\log L = -4.5$ (by interpolation) and 12 at $\log L = -5$. Lower mass cores cool even faster. The nondetection of the white dwarf in G77-61 sets $\log L < -4$, giving $t(n) < 8.8$ eons. If the white dwarf were just at the limit of detectability, at $\log L = -4.5$, $t(n) = 4$; if it has $\log L = -5$, $t(n)$ would approach zero. Thus the deduced initial primary ranges from a star of one solar mass to a massive, short-lived star and is dependent on how undetectable the white dwarf now is. It is possible that future UV or space-telescope observations will detect the white dwarf, so that the question remains open.

Using evolutionary theory alone may not be safe; we do not know Y or Z for such an old star. Perhaps more direct guidance comes from the younger globular clusters in the Magellanic Clouds which contain carbon-rich giants. Clusters with ages 0.1 eon seem not to contain such stars. Persson *et al.* (1983) find clusters with composite infrared colors dominated by carbon stars. Those with individual stellar spectroscopy confirming that they are carbon-rich giants (e.g., Aaronson and Mould 1982) are then datable by color-magnitude diagrams. Hodge (1981) gives ages of 2–4 eons from the $C-M$ diagrams; his clusters with ages 6–10 eons do not contain carbon giants. If we take $t(n) = 3$, then $t(c) = 9$ eons; the initial mass would be near 1.2 $M_\odot$, the present white-dwarf luminosity $\log L = -4.5$. The initial mass-ratio near 3 might allow the mass exchange assumed in this paper and leave a residual white dwarf of less than 0.5 $M_\odot$. The white dwarf could thus have a cooling age respectably close to the age of the halo; further attempts to detect this object or resolve the system from space are warranted.

IV. NATURE AND EVOLUTION OF G77-61

Our discovery that G77-61 is almost certainly in a binary system makes it attractive to explain its unusual abundances as a product of binary star evolution. However, the long period required by with the radial velocity data implies a separation wide enough (<0.7 a.u.) that significant prior interaction between components is not required. The star's metal-poor chemical composition and halo kinematics may be important clues to its evolutionary history as well. In the following discussion, therefore, we pursue several possible evolutionary scenarios.

a) H-R Diagram Position: Constraints on the Interior Chemical Composition

The M_v, $R-I$ diagram of Paper I showed that G77-61 lies to the blue of (or below) the Population I main sequence in the cool subdwarf region. If we utilize the refined parallax of § II (yielding $M_v = 10.08 \pm 0.43$), the $T_{\rm eff}$ estimate of § III (4100 $+{}^{+200}_{-300}$ K), and the bolometric correction of -0.96 mag, the derived bolometric luminosity is $\log (L/L_\odot) = -1.78 \pm 0.16$. The radius is of the order 0.7 $R_\odot$. G77-61 lies well below the main sequence of stars with solar-type abundance in the true H-R diagram, as shown in Figure 7. In this subsection we investigate what kind of composition is necessary to produce a star at this H-R diagram position, and we conclude that this suggests an interior composition which is extremely metal poor, helium rich, or both.

Homogeneous composition main-sequence star models can be produced at higher temperatures than Population I models by either decreasing the metals or increasing the helium. A main sequence was generated for $Z = 0.0004$ (see Fig. 7) to illustrate the effect of a drastic decrease in metals. Models by Mengel *et al.* (1979) show that further reducing the metallicity has little effect on the main-sequence position. Thus, to produce a shift to even higher temperatures, it was necessary to consider lower hydrogen abundances. Sequences are shown, down to $X = 0.3$, which bracket the "error rectangle" in $\log L$, $\log T_{\rm eff}$ for G77-61.

We found acceptable model fits for the mass range 0.4 $M_\odot$ (at $X = 0.7$) down to 0.2 $M_\odot$ ($X = 0.3$). The best fit was 0.3 $M_\odot$ at $X = 0.5$. While the surface temperature limits we have adopted thus allow a "normal" hydrogen abundance, this would require an extremely low metallicity. Thus, in the stellar

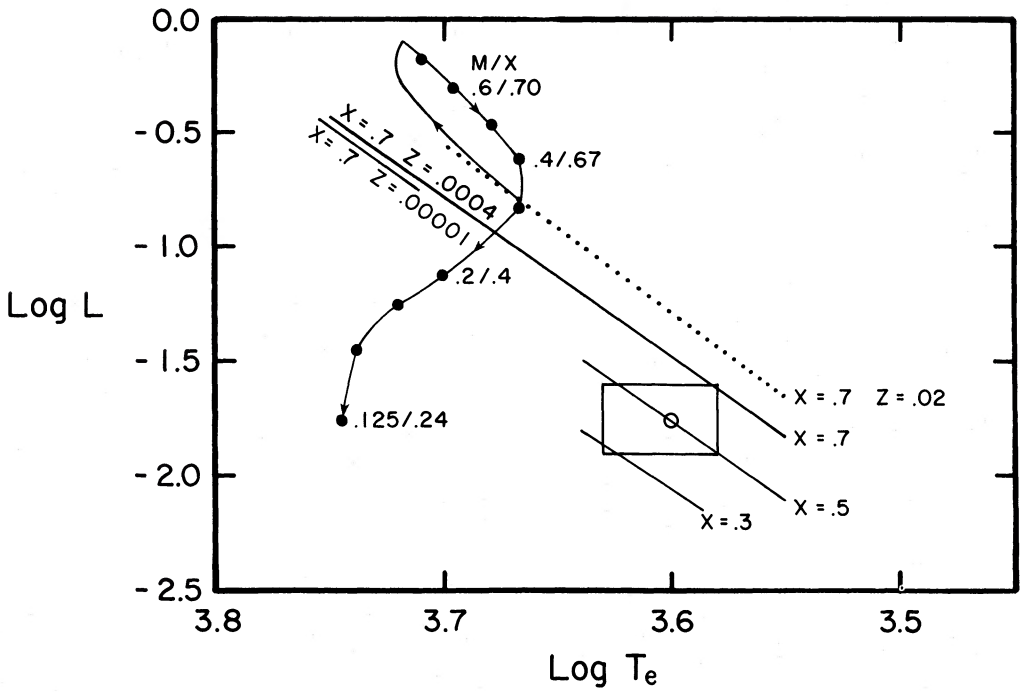

FIG. 7.—This H-R diagram shows the location of G77-61—based on our T_e, M_{bol} estimates—with respect to theoretical zero-age main sequences having $Z = 0.0004$ and $X = 0.7$, 0.5, and 0.3. Effect of reducing Z by a further factor of 40 is also illustrated. Also shown is the main-sequence evolution of a 0.75 $M_{\odot}$ model having $X = 0.7$ and $Z = 0.02$. At the end of its main-sequence evolution ($m_{core} \approx 0.019$), mass was removed to produce a series of core/envelope models (*filled circles*). Numbers given to the right of each filled circle refer to the total mass (in $M_{\odot}$) and hydrogen abundance at the surface (X) of the model. As is seen, such models are much too hot to reproduce the position of G77-61, which is shown as an open circle surrounded by the error box determined in this paper.

interiors fitting, we encounter the same possibilities presented by the lack of metallic lines and metallic hydrides: G77-61 must be extremely metal poor, if hydrogen is normal, or it may be merely moderately metal poor if helium is enriched. Unfortunately, it is necessary to perform an accurate, detailed atmospheric analysis in order to either (1) refine T_{eff} to provide a more definitive test from stellar models, or (2) distinguish the atmospheric abundances between the two cases cited above. The evolutionary paths which might lead to visible dwarfs with and without helium enrichment are quite different: it is quite difficult to account for the former; for the latter it is probably not so difficult.

b) *Core-Envelope Models with Rapid Mass Loss*

It was shown in Paper I that single star evolution could not lead to a helium- and carbon-enriched core of sufficiently low mass, temperature, and luminosity to match G77-61. However, suppose a star is stripped of its envelope near the end of its main-sequence stage because of tidal interaction with a companion. The original primary mass was greater than 0.75 $M_{\odot}$, in order for significant evolution to occur within the age of the Galaxy.

To pursue this core-envelope model hypothesis, a model of 0.75 $M_{\odot}$, $X = 0.7$, $Z = 0.02$ was evolved to the point of core hydrogen exhaustion ($m_{core} = 0.02$). Mass was then arbitrarily removed to determine the position of such a star after suffering different amounts of mass loss. This evolutionary "sequence" is shown as a series of filled circles in Figure 7, each labeled by total mass and hydrogen abundance. As is seen, the surface abundance of helium begins to increase dramatically when the mass has been reduced to 0.3 $M_{\odot}$. Additional mass loss drops the luminosity to an acceptable level, but the increased helium abundance produces models which are too hot (~5500 K). Lower Z (metal-poor) or higher mass models would fall at even higher temperatures. A low-mass star (~0.4 $M_{\odot}$) might pass through the required low-temperature region if the envelope were stripped, but such stars cannot develop a substantial helium core within the lifetime of the universe. Therefore, we do not believe that a core-envelope model can suitably represent G77-61.

c) *Binary Evolution with a Now-unseen Massive Primary*

The previous, unsuccessful hypothesis involved the assumption that the now-visible star is the primary in a binary system. A much more realistic possibility, given the results of § II, is that the original primary star in the system transferred helium- or carbon-enriched material, or both, to the star we now see, but has since faded to invisibility (presumably as a cool white dwarf). The helium abundance in our "best fit" model could be achieved by accreting helium with enhanced carbon for the spectrum onto a normal main-sequence star of 0.2 $M_{\odot}$. The composition which would have to be accreted is consistent with an R CrB primary. The metal content would have to be low, to leave G77-61 as metal poor as it now is. Static models of R CrB stars have been produced by Trimble and Paczyński (1973), and they require a carbon-oxygen white dwarf core with $M_c > 0.6$ $M_{\odot}$ consistent with the companion mass. Typical masses of R CrB stars are 2 $M_{\odot}$ (Trimble 1972), implying that the original system would have had an extreme mass ratio. However, Sparks and Stecher (1974) have shown that such a mass ratio should lead to orbital decay and result in "common envelope" evolution (Paczyński 1976; Meyer and Meyer-Hofmeister 1979; Taam, Bodenheimer, and Ostriker 1979).

In a common envelope, a 0.2 $M_{\odot}$ secondary would accrete helium at its Eddington limit ($\sim 3 \times 10^{-4}$ $M_{\odot}$ yr^{-1}) and would require ~ 300 yr to accrete 0.1 $M_{\odot}$ of helium. This is consistent with the "spin-down times" of a few hundred to a thousand years obtained by Paczyński (1976) and by Meyer and Meyer-Hofmeister (1979). The common envelope evolution would, however, terminate by envelope ejection, leaving a carbon-oxygen white dwarf ($M > 0.6$ $M_{\odot}$) in a *close binary* system with the M dwarf. This is believed to lead to the formation of cataclysmic variables and typically results in systems with periods less than 1 day. Known binary stars which are believed to have evolved through a common envelope stage but are not currently interacting include V471 Tau (Nelson and Young 1970) and LB 3459 (Paczyński 1980; Conti, Dearborn, and Massey 1981). These systems have separations ($\sim 10^{11}$ cm) and periods (6 and 12 hr) *much* shorter than the period of G77-61.

While G77-61 has apparently not undergone common envelope evolution, the clear presence of carbon in the low-mass visible component is most easily understood as a result of mass transfer from a carbon star. The long-period orbit has a Roche radius around the primary (~ 100 $R_{\odot}$), such that in the asymptotic giant branch phase it could transfer some mass. However, to avoid the spin-down associated with common envelope evolution, the envelope of the primary must have been dissipated (perhaps by ejecting a planetary nebula) before much mass was transferred. The convection zone of G77-61 contains at least 0.1 $M_{\odot}$. In order to contaminate this much mass with limited mass transfer, either the initial metal abundance of G77-61 must have been very low, or the primary must have been very carbon rich ($\sim 10\%$). If the helium in G77-61 were enhanced, however, significant mass transfer would be unavoidable, and would be difficult to reconcile with the large separation.

d) Primordial Composition Hypothesis

While the presence of a collapsed object in the system makes attractive the hypothesis of carbon contamination from mass exchange, the possibility of a very low metallicity leads us to consider the hypothesis that G77-61 represents an early stage in the chemical history of our Galaxy. The position of G77-61 on the H-R diagram requires it to be very metal-poor, consistent with its halo kinematics. The unusual composition of G77-61 might then be a Population III star characteristic; its binary nature in that case would not be directly relevant to the composition observed.

This hypothesis is unattractive because (1) it ignores the fact that G77-61 is binary and (2) because there is absolutely no precedent we are aware of for asserting that the most metal-poor stars in the galaxy have high carbon-to-oxygen ratios. On the contrary, the evidence from abundance analyses points in the opposite direction (see Clegg, Lambert, and Tomkin 1981). Finally, the hypothesis could not accommodate a helium-enriched star.

V. CONCLUSIONS

In this paper we have presented improved astrometric and spectrophotometric data on G77-61, refining its position in the H-R diagram. More critically, we have found through the discovery of radial velocity variations that it is a binary. The unseen companion is most likely a cool white dwarf, massive compared to the visible star. The separation is consistent with the hypothesis that limited mass transfer occurred. Both the absorption spectrum and the H-R diagram position indicate that the visible star is either exceedingly metal poor or moderately metal poor and helium enriched. We cannot currently choose between these two possibilities, which carry different evolutionary implications.

The most straightforward explanation is that G77-61 has an extremely metal poor composition and accreted a small amount of carbon-rich material when the original primary was at maximum radius; this inverted the carbon-to-oxygen ratio in the low-mass star. We cannot, however, absolutely rule out that the star could simply have formed with such a CO ratio as a very early halo object. Should an atmospheric abundance analysis prove that helium is enriched in the object, it would be necessary to argue that substantial mass transfer (>0.1 $M_{\odot}$) occurred to produce the observed abundances. A large amount of mass transfer would be consistent with common envelope evolution conflicting with the long period.

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REFERENCES

Aaronson, M. 1983, *Ap. J. (Letters)*, **266**, L11.
Aaronson, M., and Mould, J. 1982, *Ap. J. Suppl.*, **48**, 161.
Ake, T. B., and Greenstein, J. L. 1980, *Ap. J.*, **240**, 859.
Carbon, D. F., Langer, G. E., Butler, D., and Kraft, R. P. 1982, *Ap. J. Suppl.*, **49**, 207.
Clegg, R. E. S., Lambert, D. L., and Tomkin, J. 1981, *Ap. J.*, **250**, 262.
Cohen, J., Frogel, J., Persson, S. E., and Elias, J. 1981, *Ap. J.*, **249**, 481.
Conti, P. S., Dearborn, D., and Massey, P. 1981, *M.N.R.A.S.*, **195**, 165.
Dahn, D., Liebert, J., Kron, R. G., Spinrad, H., and Hintzen, P. M. 1977, *Ap. J.*, **216**, 757.
Dahn, C., and Priser, J. B. 1973, *A.J.*, **78**, 253.
Frogel, J. A., Persson, S. E., Aaronson, M., and Matthews, K. 1978, *Ap. J.*, **220**, 75.
Gass, H., Wehrse, R., and Liebert, J. 1985, in preparation.
Greenstein, J. L. 1984, *Ap. J.*, **276**, 602.
Greenstein, J. L., and Eggen, O. J. 1966, in *Vistas in Astronomy*, Vol. **8**, ed. A. Beer (Oxford: Oxford Press), p. 63.
Hodge, P. W. 1981, *Ap. J.*, **247**, 894.
McClure, R. D. 1982, private communication.
Mengel, J., Sweigart, A., Demarque, P., and Gross, P. 1979, *Ap. J. Suppl.*, **40**, 733.
Meyer, F., and Meyer-Hofmeister, E. 1979, *Ap. J.*, **78**, 167.
Mould, J. 1976, *Ap. J.*, **207**, 535.
Mould, J., Cannon, R. D., Aaronson, M., and Frogel, J. A. 1982, *Ap. J.*, **254**, 500.
Mould, J., and Hyland, A. R. 1976, *Ap. J.*, **208**, 399.
Nelson, B., and Young, A. 1970, *Pub. A.S.P.*, **82**, 699.
Oke, J. B. 1974, *Ap. J.*, *Suppl.*, **27**, 21.
Paczyński, B. 1971, *Ann. Rev. Astr. Ap.*, **9**, 183.
———. 1976, in *IAU Symposium 73*, *The Structure and Evolution of Close Binary Systems*, ed. P. Eggleton, S. Mitton, and J. D. Whelan (Dordrecht: Reidel), p. 75.
———. 1980, *Acta Astr.*, **30**, 113.
Persson, S. E., Aaronson, M., and Frogel, J. A. 1977, *A.J.*, **82**, 729.
Persson, S. E., Aaronson, M., Cohen, J. G., Frogel, J. A., and Matthews, F. 1983, *Ap. J.*, **266**, 105.
Shaviv, G., and Kovetz, A. 1976, *Astr. Ap.*, **51**, 383.
Smak, J., and Wing, R. F. 1979, *Acta Astr.*, **29**, 187.

Sparks, W. M., and Stecher, T. P. 1974, *Ap. J.*, **188**, 149.
Taam, R. E., Bodenheimer, P., and Ostriker, J. P. 1979, *Ap. J.*, **222**, 264.
Tonry, J., and Davis, M. 1979, *A.J.*, **84**, 1511.
Trimple, U. L. 1972, *M.N.R.A.S.*, **156**, 411.
Trimple, U. L., and Paczyński, B. 1973, *Astr. Ap.*, **22**, 9.
VandenBerg, D. A. 1983, *Ap. J. Suppl.*, **51**, 29.
Wing, R. 1967, Ph.D. thesis, University of California at Berkeley.

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