derive the initial luminosity $L$ from $L = L^* / (f_{\text{sim}} / C_{\text{sim}})$, where $L^* = 350 L_\odot$ is the total luminosity of the giants in the clump in our near-complete sample, $f_{\text{sim}} \approx 0.13$ is the ratio of the luminosity in giants with $M_{\text{f}}$ and $(B - V)$ in the range observed to the total luminosity of the system for an old metal-poor stellar population, $C_{\text{sim}} = 0.92$ is our estimated completeness, and $f_{\text{sim}} \approx 1.9 \times 10^{-4}$ is the fraction of the initial satellite contained in a sphere of 1 kpc radius around the Sun as determined from our simulations. This gives $L \approx 1.5 \times 10^3 L_\odot$, from which we can derive, using our previous estimates of the initial velocity dispersion and core radii, an average initial core mass-to-light ratio $M/L \approx 3 - 10 T_\odot$, where $T_\odot$ is the mass-to-light ratio of the Sun. A progenitor system with these characteristics would be similar to Fornax. Moreover, the mean metal abundance of the stars is consistent with the derived luminosity, if the progenitor follows the known metallicity–luminosity relation of dwarf satellites in the Local Group\(^9\).

The precursor object was apparently on an eccentric orbit with a relatively large apocentre. Given that it contributes 7/97 of the local halo population, our simulations suggest that it should account for 12% of all metal-poor halo stars outside the solar circle. Figure 2 shows that there are few other halo stars on high angular momentum polar orbits in the solar neighbourhood, just the opposite of the observed kinematics of satellites of the Milky Way\(^6\). The absence of satellite galaxies on eccentric non-polar orbits argues that some dynamical process preferentially destroys such systems; their stars should then end up populating the stellar halo. As we have shown, the halo does indeed contain fossil streams with properties consistent with such disruption.

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**Multiple stellar populations in the globular cluster \(\omega\) Centauri as tracers of a merger event**


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The discovery of the Sagittarius dwarf galaxy\(^1\), which is being tidally disrupted by and merging with the Milky Way, supports the view that the halo of the Galaxy has been built up at least partially by the accretion of similar dwarf systems. The Sagittarius dwarf contains several distinct populations of stars\(^2\), and includes M54 as its nucleus, which is the second most massive globular cluster associated with the Milky Way. The most massive globular cluster is \(\omega\) Centauri, and here we report that \(\omega\) Centauri also has several distinct stellar populations, as traced by red-giant-branch stars. The most metal-rich red-giant-branch stars are about 2 Gyr younger than the dominant metal-poor component, indicating that \(\omega\) Centauri was enriched over this timescale. The presence of more than one epoch of star formation in a globular cluster is quite surprising, and suggests that \(\omega\) Centauri was once part of a more massive system that merged with the Milky Way, as the Sagittarius dwarf galaxy is in the process of doing now. Mergers probably were much more frequent in the early history of the Galaxy and \(\omega\) Centauri appears to be a relic of this era.

As part of our investigation of the luminosity–metallicity relation of the RR Lyrae stars in the globular cluster \(\omega\) Cen, we have obtained 2K BV CCD (charge-coupled device) frames with the CTIO 0.9-m

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**Figure 1** Colour–magnitude diagram of 50,129 stars in the direction of \(\omega\) Cen. These data were obtained from a mosaic of nine 2K CCD (charge-coupled device) fields. Only stars with at least 20 detections and small photometric errors ($\sigma_L < 0.05$ mag and $\sigma_{B-V} < 0.07$ mag) have been plotted. a, All stars in our programme field; b, stars located between 2.58 and 15.48 arcmin from the cluster centre. There are several distinct RGBs and a red clump associated with the most metal-rich component. Two RGB loci from the new Yale isochrones\(^2\) (metallicity $Z = 0.0004$, 0.005) are also compared (b, solid lines) that bracket the metallicity range of \(\omega\) Cen. $M_V$, absolute visual magnitude.
telescope that cover $40 \times 40$ arcmin$^2$ in a $3 \times 3$ grid centred on the cluster, and covering out to approximately half the tidal radius. In total, 40–42 frames were taken in each filter and each field. The seeing was between 1.0 and 1.7 arcsec, and all of the observing nights (5–10 April 1996) were fully photometric. The $B$ and $V$ magnitudes of individual stars were measured with the point-spread-function (PSF)-fitting programs DAOPHOT II and ALLSTAR in the standard manner. As a by-product of this investigation, we obtained high-quality homogeneous $BV$ colour–magnitude data for more than 130,000 stars in the field toward $\omega$ Cen, which represents the most extensive photometric survey to date for this cluster.

Figure 1 shows a $V$ versus $B – V$ colour–magnitude diagram for stars in our programme field. We note the presence of several distinct red-giant branches (RGBs) with a red, presumably metal-rich, sequence well separated from other bluer metal-poor ones. This feature was not evident in previous photometry with smaller sample sizes and larger photometric uncertainties. The radial distribution of the most metal-rich RGB stars is not significantly different from those of the metal-poor ones, which confirms that they belong to $\omega$ Cen. Note also that the red clump that must be associated with the most metal-rich RGB is clearly apparent, partially overlapping the metal-poor RGBs. The presence of other interesting features on the colour–magnitude diagram, such as the blue-tail phenomenon of the horizontal-branch and the blue straggler stars, illustrates the diversity of stellar populations in this cluster. The signature of field-star contamination is also evident, primarily as a swathe of stars with $0.3 \lesssim (B – V) \lesssim 1.2$. These stars will belong to the foreground galactic disk population.

In order to further investigate the discrete nature of the RGB, we have plotted in Fig. 2 a histogram of the distribution of colour difference between each RGB star and the RGB fiducial of the most metal-poor component. The RGB stars are selected in a relatively narrow magnitude range $12.4 < V < 12.9$, so that the field-star and red-clump contamination is minimized, and which also avoids artificial mixing in the histogram stemming from metallicity dependence of the RGB slope. The presence of several distinct RGBs is confirmed, although the most metal-rich component is not as well distinguished as in Fig. 1 because of the small sample size of such stars in this magnitude range.

Figure 3 shows our population models. These illustrate the relative age estimation from the location of the red clump associated with the most metal-rich RGB with respect to blue horizontal-branch stars associated with the most metal-poor component. Figure 3a shows the case where all stars have the same age despite their different metallicities, which produces a red horizontal branch that is clearly much bluer than the observed red clump confined within the two most extreme RGBs. Figure 3b shows our best match with the observed colour–magnitude diagram in Fig. 1, which suggests that the most metal-rich population in $\omega$ Cen is some 2 Gyr younger than the most metal-poor population. Only a $\Delta t$ of about 2 Gyr reproduces the features on the observed colour–magnitude diagram in Fig. 1.

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Figure 2 Histogram of the distribution of colour difference. Colour difference between each RGB star and the RGB fiducial of the most metal-poor component, $\Delta(B – V)$, is plotted in the range $12.4 < V < 12.9$. The metallicities ($Z$ values) of four distinct RGBs are also marked.

Figure 3 Stellar population models. The models illustrate the estimation of age difference between the red clump associated with the most metal-rich ($Z = 0.005$) RGB and the blue horizontal-branch associated with the most metal-poor ($Z = 0.0004$) component. Dots and crosses are individual horizontal-branch stars from synthetic horizontal-branch models and the solid lines are from new Yale isochrones. a, All stars have the same age despite their different metallicities; b, the most metal-rich population is 2 Gyr younger than the most metal-poor population. Only a $\Delta t$ of about 2 Gyr reproduces the features on the observed colour–magnitude diagram in Fig. 1.
Gravitational microlensing events are observed via the time-varying magnification of the sum of the gravitationally lensed images as the lens system passes in front of the background source star. The separation of the images is too small to observe with current instruments. A planet orbiting the lens star can be detected by a brief deviation of the microlensing light curve from the normal single lens light curve.

The microlensing event MACHO-97-BLG-41 was discovered by the MACHO team and announced on 19 June 1997. MPS observations from the Mt Stromlo 1.9-m telescope began on that night. On 29 June, the MACHO team issued a further announcement that the light curve of this event did not have the shape expected for a single lens event, and the PLANET team issued a similar announcement on 2 July. Regular observations by the GMAN follow-up team began shortly after this second MACHO announcement, with nightly observations from the CTIO 0.9-m telescope and less frequent observations from the Wise Observatory 1.0-m telescope. The MACHO and GMAN data were previously presented without analysis by the MACHO/GMAN group. Here we present a combined analysis of the MPS and MACHO/GMAN data. The modelling of MACHO-97-BLG-41 has proven to be more difficult than any other multiple lensing event observed by MACHO/GMAN or MPS to date. Figure 1 shows the light curve of the combined data set along with the best-fit model, while Fig. 2

### Discovery of a planet orbiting a binary star system from gravitational microlensing

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The properties of the recently discovered extrasolar planets were not anticipated by theoretical work on the formation of planetary systems, most models for which were developed to explain our Solar System. Indeed, the observational technique used to detect these planets (measurement of radial-velocity shifts in stellar spectral lines) do not yet have the sensitivity to detect planetary systems like our own. Here we report observations and modelling of the gravitational microlensing event MACHO-97-BLG-41. We infer that the lens system consists of a planet of about 3 Jupiter masses orbiting a binary stellar system consisting of a late-K dwarf star and an M dwarf. The stars are separated by ~1.8 astronomical units (1 AU is the Earth–Sun distance), and the planet is orbiting them at a distance of about 7 AU. We had expected to find first the microlensing signature of jovian planets around single stars, so this result suggests that such planets orbiting short-period binary stars may be common.

The Microlensing Planet Search (MPS) Collaboration aims to detect planets that orbit distant stars by detecting the influence of such planets on the light curves of gravitational microlensing events.

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**Figure 1** The light curve and best-fit model for the MACHO-97-BLG-41 microlensing event as a function of time. The data consist of 356 MPS R-band observations from the Mt Stromlo 1.9-m telescope, 197 MACHO-R and 194 MACHO-V band observations from the Mt Stromlo 1.3-m telescope, 35 R-band observations from the CTIO 0.9-m telescope, and 17 R-band observations from the Wise 1.0-m telescope. The MACHO-R, MACHO-V, Wise-R, CTIO-R and MPS data are plotted in red, blue, green, cyan and magenta, respectively. Insets show close-ups of the caustic crossing regions of the light curves; the tick intervals for these figures is 1 day. The last 5 observations from the night of 20 June were short exposures taken in bright moonlight over a span of 40 min. These have been averaged into a single data point for the inset at upper left. The MPS and MACHO data were reduced with ALLFRAME. The solid curve is the best-fit triple lens model described in the text, and the dashed curve in the inset figures is the ‘best fit’ orbiting binary lens light curve which requires an ‘orbital velocity’ larger than the escape velocity of the binary system and is therefore unphysical. This large orbital velocity is due to the large distance that the binary stars must move to account for both caustic crossing features and the small $r_e$ value for this fit which is required to achieve the magnifications observed on 20–21 June.