THE STAR FORMATION HISTORY AND SPATIAL DISTRIBUTION OF STELLAR POPULATIONS IN THE URSA MINOR DWARF SPHEROIDAL GALAXY

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ABSTRACT

As a part of a project devoted to the study of the Ursa Minor dwarf spheroidal (dSph) galaxy, the star formation history of the galaxy is presented. The analysis uses wide-field photometry, encompassing about 1° × 1° (the total covered area being 0.75 deg²), which samples the galaxy out to its tidal radius. Derivation of the star formation history (SFH) has been performed using the synthetic partial-model technique. The resulting SFH shows that Ursa Minor hosts a predominantly old stellar population, with virtually all the stars having formed earlier than 10 Gyr ago and 90% having formed more than 13 Gyr ago. Nevertheless, the Ursa Minor color-magnitude diagram shows several stars above the main, old turnoff forming a blue plume (BP). If these stars were genuine main-sequence stars, Ursa Minor would have maintained a low star formation rate extending up to ~2 Gyr ago. However, several indications (relative amount and spatial distribution of BP stars and difficulty of retaining processed gas) argue against this possibility. In such a context, the most reliable hypothesis is that BP stars are blue stragglers originating in the old population, with Ursa Minor hence remaining the only Milky Way dSph satellite to host a pure old stellar population. A marginally significant age gradient is detected, in the sense that stars in outer regions are slightly younger on average. The distance of Ursa Minor has been calculated using the magnitude of the horizontal branch and a calibration based on Hipparcos data for main-sequence subdwarfs. We estimate a distance of 76 ± 4 kpc, which is slightly higher than previous estimates. From the red giant branch color, we estimate a metallicity [Fe/H] = −1.9 ± 0.2, in agreement with a previous spectroscopic determination. No metallicity gradients have been detected across the galaxy.

Key words: galaxies: dwarf — galaxies: fundamental parameters — galaxies: individual (Ursa Minor) — galaxies: stellar content — galaxies: structure

1. INTRODUCTION

Dwarf spheroidal (dSph) galaxies are objects of great cosmological significance. In generic hierarchical clustering scenarios for galaxy formation, such as cosmologies dominated by cold dark matter (White & Rees 1978; Blumenthal et al. 1984; Dekel & Silk 1986), dwarf galaxies should have formed prior to the epoch of giant galaxy formation and would be the building blocks of larger galaxies. The dSph galaxies observed today would be surviving objects that have not merged into larger galaxies. Therefore, unveiling their underlying structure could provide important clues about processes of dwarf galaxy formation that are now observed at high redshifts. Local Group galaxies offer the only opportunity of studying their evolution in great detail through observations of their resolved stellar populations, which are fossil records of the star formation history (SFH).

Dwarf spheroidal companions of the Milky Way were historically considered to be old systems inhabited by globular cluster–like, Population II stars (Baade 1963). However, later work revealed traces of intermediate-age stars, such as carbon stars (Aaronson & Mould 1980; Mould et al. 1982; Frogel et al. 1982; Azzopardi, Lequeux, & Westerlund 1986) and bright asymptotic giant branch stars (Elston & Silva 1992; Freedman 1992; Lee, Freedman, & Madore 1993; Davidge 1994; but see also Martínez-Delgado & Aparicio 1997). More recent studies, based on the analysis of color-magnitude diagrams (CMDs) using synthetic CMDs, have shown that dSph galaxies are objects with complex and varied SFHs (Mighell 1997; Martínez-Delgado, Gallart, & Aparicio 1999b; Gallart et al. 1999; Hernández, Gilmore, & Valls-Gabaud 2000; Aparicio, Carrera, & Martínez-Delgado 2001), and the idea that no two dSph galaxies could be identified to have similar SFHs has become popular.

As part of a larger project devoted to the study of the Ursa Minor dSph galaxy (see Martínez-Delgado et al. 2001, 2002), we present in this paper the results on the SFH of this galaxy. Our data sample the galaxy out to 40' from its center, which is on the order of its tidal radius (see Irwin & Hatzidimitriou 1995; Kleyna et al. 1998; Martínez-Delgado et al. 2001). Ursa Minor is the second-closest dSph satellite of the Milky Way (d = 69 kpc) and was discovered in the Palomar survey by Wilson (1955). Previous works have shown an old system similar, in age and abundance, to the ancient metal-poor Galactic globular cluster M92 (Olszewski & Aaronson 1985; Mighell & Burke 1999) and owning a well-populated, predominantly blue horizontal branch (see, e.g.,

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Cudworth, Olszewski, & Schommer 1986; Kleyna et al. 1998). Martinez-Delgado & Aparicio (1998) pointed out the possibility that a marginal intermediate-age stellar population could exist in the galaxy, associated with the blue plume present in its CMD. Olszewski & Aaronson (1985) and Mighell & Burke (1999) derived distance moduli of \((m - M)_0 = 19.0 \pm 0.1\) and \((m - M)_0 = 19.18 \pm 0.12\), respectively, from a sliding fit to the M92 ridgeline. As for the metallicity, it has been recently estimated by Shetrone, Côté, & Sargent (2001), from spectroscopic measurements of giant stars, to be \([\text{Fe}/\text{H}] = -1.9 \pm 0.11\).

Martinez-Delgado et al. (2001) have presented evidence that Ursa Minor is in a process of tidal disruption. This motivates the spatially extended study of the SFH that we present here. Before this, Hernández et al. (2000; see also Valls-Gabaud, Hernández, & Gilmore 2000) obtained the SFH for the very central part of Ursa Minor using deep but small-field (~2.5 × 2.5) Hubble Space Telescope data. They find a stellar population mainly composed of stars older than 10 Gyr.

The paper is organized as follows: In § 2, the observations and photometric reduction are presented. In § 3, the CMD of Ursa Minor is discussed, followed by an estimation of the distance and metallicity. The rest of the paper is mainly devoted to the derivation of the SFH and the discussion of possible evolution scenarios for Ursa Minor, to which §§ 4, 5, and 6 are devoted. Finally, the main results of the paper are summarized in § 7.

2. OBSERVATIONS AND DATA REDUCTION

The observations of Ursa Minor were carried out in \(B\), \(V\), \(R\), and \(I\) Johnson-Cousins filters with the 2.5 m Isaac Newton Telescope (INT) at Roque de los Muchachos Observatory in La Palma and with the 0.8 m IAC-80 telescope at Roque de los Muchachos Observatory. At the INT, we used the Wide Field Camera (WFC) installed at the prime focus, which holds four 2048 × 4096 pixel EEV chips. The scale is 0.′33 pixel−1, which provides a total field of about 35′ × 35′. Three fields were observed in \(B\) and \(R\) filters encompassing a region of about 1° × 1°, with a total covered area of about 0.75 deg2. Table 1 provides a summary of the observations. Figure 1 shows the observed fields. The field containing the center of the galaxy (field A) was also observed in \(V\) and \(I\). These data will be used to estimate the distance and metallicity (see § 3). Observations with the IAC-80 telescope were made to obtain the standard transformations for these bands. A Thomson 1024 × 1024 chip was used with a scale of 0.′43 pixel−1, covering a total area of nearly 7.5′ × 7.5′.

The images were processed in the usual way. Bias and flat-field corrections were performed with IRAF, DAOPHOT and ALLSTAR (Stetson 1994) were used to obtain the photometry of the resolved stars. Transformation into the standard photometric system requires several observations of standard-star fields in such a way that standards are measured in all four chips of the WFC. In practice, we observed three fields from Landolt (1992) in the four chips and used them to calculate relative photometric transformations from each chip to the central one (chip 4). Then a larger number of standard-star fields were measured in chip 4 during the observing run to calculate both nightly atmospheric extinctions and the general transformation into the standard Johnson-Cousins system. In total, 170 measurements of 38 standards were made during the observing run of 1998 May. Summarizing, the transformations from each chip to chip 4 are

\[
\begin{align*}
b_4 - b_1 &= 0.329 + 0.02(B - R), \quad \sigma = 0.005; \\
b_4 - r_1 &= 0.837 - 0.307(B - R), \quad \sigma = 0.010; \\
b_4 - b_2 &= 0.443 - 0.006(B - R), \quad \sigma = 0.007; \\
r_4 - r_2 &= 0.833 - 0.268(B - R), \quad \sigma = 0.008; \\
b_4 - b_3 &= 0.367 + 0.021(B - R), \quad \sigma = 0.008; \\
r_4 - r_3 &= 0.739 - 0.233(B - R), \quad \sigma = 0.008; 
\end{align*}
\]

where subscripts refer to chips, lowercase letters stand for instrumental magnitudes, and capital letters stand for Johnson-Cousins magnitudes. The \(\sigma\)-values correspond to the fit dispersion at the barycenter of the point distribution; hence they place lower limits on the zero-point errors.

Transformations from chip 4 instrumental magnitudes measured at the top of the atmosphere into Johnson-Cousins magnitudes are given by

\[
\begin{align*}
B - b_4 &= 24.553 - 0.061(B - R), \quad \sigma = 0.009; \\
R - r_4 &= 24.393 + 0.257(B - R), \quad \sigma = 0.010; 
\end{align*}
\]

where, as before, lowercase letters refer to extinction-free, instrumental magnitudes and capital letters to Johnson-Cousins magnitudes.
The central field (field A in Fig. 1) of Ursa Minor was also observed with the INT in $V$ and $I$ in 1999 June. This run was not photometric, and thus the IAC-80 telescope was used in 2001 May to obtain the photometric calibration. Fifteen standards from Landolt (1992) and several secondary standards defined in the central region of Ursa Minor (covered by chip 4 in the INT observations) were observed to this aim with the IAC-80. The resulting transformation equations for the IAC-80 were

$$V - V_{IAC-80} = 21.110 + 0.055(V - I), \quad \sigma = 0.009; \quad (9)$$
$$I - i_{IAC-80} = 21.064 + 0.076(V - I), \quad \sigma = 0.006; \quad (10)$$

while the final transformation for the INT observations (chip 4) were

$$V - V_4 = 24.13 + 0.04(V - I), \quad \sigma = 0.02; \quad (11)$$
$$I - i_4 = 24.21 + 0.02(V - I), \quad \sigma = 0.02. \quad (12)$$

As above, lowercase letters refer to instrumental magnitudes and capital letters to Johnson-Cousins magnitudes.

Finally, dispersions of the extinctions for each night are about $\sigma = 0.01$ for each filter. Aperture corrections were obtained using a set of $\sim 200$ isolated, bright stars in the Ursa Minor frames, dispersions being of order $\sigma = 0.01$. Putting all the errors together, the total zero-point error of our photometry can be estimated to be about $\sigma = 0.02$ for all bands.

In addition to these errors, ALLSTAR provides, for each star, the dispersion $\sigma$ of the point-spread function (PSF) fitting. Generally, these residuals do not reproduce the external errors of the photometry (see Aparicio & Gallart 1995; Gallart, Aparicio, & Vílchez 1996), but they are an indication of the internal accuracy of the photometry. Figure 2 shows these residuals as a function of magnitude for each star. For the final photometric list we selected stars with $\sigma < 0.25$.

Artificial-star tests were performed in the usual way (Stetson & Harris 1988; see also Aparicio & Gallart 1995) to obtain completeness factors as a function of magnitude. In short, 13,000 artificial stars were added to the $B$ and $R$ images of Ursa Minor. The central chip (chip 4) of the...
central field was used. These stars were distributed in a grid covering the whole image. To avoid overcrowding effects, they were separated about 8.5′ from each other. Colors and magnitudes chosen for artificial stars were obtained from the synthetic CMD (computed as described in Aparicio & Gallart 1995) of an old stellar population with similar metallicity to Ursa Minor. The resulting completeness factors are shown in Figure 3. Completeness peaks at “V” ≈ 23.5, but about 5%–10% of stars are lost at any brighter magnitude. These stars are those happening to lie close to very bright, saturated stars.

3. COLOR-MAGNITUDE DIAGRAM

Figure 4 shows the (B−R, “V”) CMD of the inner (a ≤ 18′) and outer (18′ < a ≤ 40′) regions of Ursa Minor [with “V” defined as (B + R)/2]. It must be noted that stars associated with Ursa Minor exist at galactocentric distances larger than 40′. We restrict our plot to stars within this distance to limit foreground and background contamination (see Martínez-Delgado et al. 2001 for more details, including CMDs for the outermost regions). Figure 5 shows a map of the resolved stars, with the ellipses limiting the inner and outer regions overplotted. The galaxy center, the ellipses’ ellipticity (1 − b/a = 0.44) and the position angle (53°) were chosen following Irwin & Hatzidimitriou (1995).

The two CMDs shown in Figure 4 are qualitatively similar. The most noticeable features are the faint, main turnoff at “V” ≈ 23 and B−R ≈ 0.8; the blue plume extending above it and reaching “V” ≈ 21.2; a well-populated, globular cluster–like, narrow red giant branch (RGB); and a predominantly blue horizontal branch (HB), including several stars in the RR Lyrae instability strip. All this suggests an old, low-metallicity stellar population and a small metallicity dispersion. However, the blue plume requires more attention because it could be made of blue stragglers, but it could also be the trace of an intermediate-age population. It will be discussed in § 5.

Figure 6 shows the (V−I, V) and (V−I, I) CMDs of stars in the central chip of field A. Although shallower and less populated than the (B−R, “V”) CMD, they are better suited for the estimation of distance and metallicity and will be used for this purpose in the following sections.

Fig. 2.—Residuals of the PSF-to-star fitting as a function of magnitude, provided by ALLSTAR, for the stars resolved in the Ursa Minor frames.

Fig. 3.—Completeness factor as a function of “V” for the central chip of field A (see Fig. 1). “V” is defined as (B + R)/2.

Fig. 4.—CMDs of the inner and outer regions of Ursa Minor. Top, stars within a ≤ 18′; bottom, stars within 18′ < a ≤ 40′.
3.1. Distance

The distance to Ursa Minor can be calculated from the HB magnitude at the color of the RR Lyrae variables. A relation between [Fe/H] and $M_V$ for RR Lyrae must be assumed for this purpose. However, Demarque et al. (2000) have shown that such a relation is not universal and depends on the HB morphology. To overcome this problem, we have compared Ursa Minor’s HB with that of several globular clusters with similar metallicity and HB morphology to the galaxy. The distance to Ursa Minor can then be obtained from the difference in magnitude between cluster and galaxy HBs and the cluster distances.

For this purpose, we first need an estimate of Ursa Minor’s metallicity and of its HB $V$ magnitude. The metallicity has been estimated using the color of the RGB and the Carretta & Gratton (1997, hereafter CG) and Zinn & West (1984, hereafter ZW) scales (see § 3.2). The first, $[\text{Fe/H}] = \frac{C_0}{1.75}$, will be adopted here, since the metallicities of the globular clusters used for comparison are given in the CG scale.

The Ursa Minor HB $V$ magnitude must be a reddening-free value, which we will denote $V_{UMi}^{HB,0}$; obtained approximately for the center of the RR Lyrae instability strip, that is, at about $V-I = 0.4$. The HB “$V$” magnitudes must first be transformed into the usual Johnson $V$ magnitudes. This has been accomplished with the same Padua stellar evolution models (Bertelli et al. 1994) used in § 4. The average difference for the interval $0.2 \leq B-R \leq 0.6$ is $V-\langle V \rangle = -0.031 \pm 0.002$. Then an empirically defined fiducial HB taken from Rosenberg et al. (1999) was fitted to the Ursa Minor HB. It produces $V_{HB}^{UMi} = 19.84 \pm 0.07$. Furthermore, using the infrared dust maps by Schlegel, Finkbeiner, & Davis (1998), a reddening of $E(B-V) = 0.034$ is obtained for Ursa Minor. Assuming the relations from Cardelli, Clayton, & Mathis (1989), this corresponds to an extinction $A_V = 0.104$, from which $V_{UMi}^{HB,0} = 19.74 \pm 0.07$ results.

The clusters selected for the HB comparison are listed in Table 2. They have been taken from the IAC-Padua catalog of Galactic globular clusters (CGGC; Rosenberg et al. 2000a, 2000b). Column (1) gives the cluster name. Column (2) lists the metallicity in the CG scale. The reddening-free distance moduli and HB magnitudes are given in columns (3) and (4). These values are estimated from main-sequence fitting to Hipparcos subdwarfs (Reid 1999 and references therein). Although clusters with similar metallicity to Ursa Minor have been chosen, small differences are still present. To avoid the effects of these differences, the globular cluster HB magnitudes have been transformed to those corresponding to the galaxy metallicity using $V_{HB,0}^{gc} = V_{HB,0}^{UMi} + 0.18([\text{Fe/H}]_{UMi} - [\text{Fe/H}]_{bc})$. The resulting magnitudes are given in column (5). Column (6) lists the reddening-free magnitude differences between Ursa Minor and cluster HBs: $\Delta V_{HB,0} = V_{HB,0}^{UMi} - V_{HB,0}^{bc}$. Finally, column (7) gives the distance moduli obtained for Ursa Minor as $(m-M)_{0}^{UMi} = (m-M)_{0}^{bc} + \Delta V_{HB,0}$. The average of the values listed in Table 2, column (7), is $(m-M)_{0} = 19.4 \pm 0.1$, corresponding to $d = 76 \pm 4$ kpc. This value is larger than the value $(m-M)_{0} = 19.24 \pm 0.24$ given by Nemec et al. (1988) using RR Lyrae periods. Comparing Ursa Minor and M92 fiducial sequences, Mighell & Burke (1999) and Olszewski & Aaronson (1985) derived distance moduli of $(m-M)_{0} = 19.18 \pm 0.12$ and
(m - M)₀ = 19.0 ± 0.1, respectively, also smaller than our result.

3.2. Metallicity

The metallicity of Ursa Minor has been measured spectroscopically by Shetrone et al. (2001), who provided a mean value of [Fe/H] = −1.90 ± 0.11. Previously, Olzewska & Aaronson (1985) photometrically estimated it to be about [Fe/H] = −2.2, assuming that Ursa Minor has the same metallicity and age as M92. Here we will provide a new photometric estimate, based on the color of the RGB. This is a frequently used estimator because photometrically observing and measuring the RGB is a relatively simple task. However, it is clear that this method cannot compete with spectroscopic determinations, and recently, Gallart (2002) has shown that these RGB estimates can be far off. In any case, the metallicity that we derive will at least be useful for comparison with results for other galaxies existing in the literature obtained with the same method.

To estimate the metallicity, we have used the relations provided by Saviane et al. (2000), based on the position of the RGB of several globular clusters from the CGGC (Rosenberg et al. 2000a, 2000b). We will use the calibration based on the parameter (V - I)_{F = -3} that is, the V - I color index of the RGB at M_F = −3. From Figure 6, we estimate (V - I)_{F = -3} = 1.17 ± 0.03. The resulting metallicity is [Fe/H] = −1.75 ± 0.20 if the CG metallicity scale is used, or [Fe/H] = −2.01 ± 0.14 if the ZW metallicity scale is used. Considering both values, we adopt [Fe/H] = −1.9 ± 0.2, which agrees with the spectroscopic value.

The color of the RGB can be also used to test whether galactocentric metallicity gradients exist in Ursa Minor, under the reasonable assumption that age gradients, if any, have negligible effects on the RGB color. To this purpose, the galaxy has been divided into several concentric elliptical annuli and the (B − R, R) CMDs have been plotted for them. The B − R plane is used now because of the larger spatial coverage obtained in the observations with these filters. Hyperbolic polynomial fits to points in the interval −1.5 ≤ R ≤ −3.2 were used to obtain a fiducial RGB for each CMD. The B − R color at M_R = −2.5 [(B − R)_{R = −2.5}] was then used as an estimator of the metallicity (Aparicio et al. 2001). It was measured for each fit, and the results are plotted in Figure 7. The error bars show the internal dispersions of points about the polynomial fits. Inspection of this figure reveals that no metallicity gradient can be deduced to exist in Ursa Minor.

4. STAR FORMATION HISTORY

The SFH of a galaxy can be derived in detail from a deep CMD through comparison with synthetic CMDs (Aparicio 2002). To obtain the SFH of Ursa Minor, we have used here the partial model method, introduced by Aparicio, Gallart, & Bertelli (1997). We have closely followed the prescriptions and criteria used by Aparicio et al. (2001), where this method was applied to derive the SFH of the Draco dSph galaxy. Details on the computation of synthetic CMDs and on the SFH computation method itself can be found in Gallart et al. (1999) and in Aparicio et al. (1997), as well as in Aparicio (2002), where different methods are reviewed.

The SFH can be considered a function of several variables (time, stellar mass, etc.). A typical approach is to assume that it is composed of the star formation rate (SFR) function ψ(t) and a chemical enrichment law Z(t). But the initial mass function (IMF) φ(m) and a function to account for the fraction and mass distribution of binary stars, β(f, q), are also relevant. The most powerful methods now in use are able to solve for ψ(t) and Z(t) simultaneously and to treat φ(m) and β(f, q) as inputs (see Aparicio 2002 and references therein). In our case, to simplify, and given Ursa Minor’s low metallicity and low metallicity dispersion, we have fixed Z(t) and solved for ψ(t) alone. We adopted the Kroupa, Tout, & Gilmore (1993) IMF and have neglected the contribution from binary stars.

The metallicity given in § 3.2, [Fe/H] = −1.9 ± 0.11 (Shetrone et al. 2001), corresponds to Z = (2.5 ± 0.5) × 10^{-4}. We have adopted a constant metallicity law with this value, but allowing some dispersion, to compute the synthetic stars. According to this law, synthetic stars have metallicities randomly distributed in the interval 2 × 10^{-4} ≤ Z ≤ 3 × 10^{-4}, independent of age. This pro-

| Cluster          | Metallicity | (m - M)₀ | (m - M)₀ | V_{HI0} | V_{HI0} | ΔV_{HI0} | (m - M)₀ |
|------------------|-------------|----------|----------|---------|---------|----------|----------|
| NGC 4590...      | −2.00 ± 0.03| 15.23 ± 0.16| 15.63 ± 0.1 | 15.67 ± 0.13 | 4.10 ± 0.15 | 19.33 ± 0.2 |
| NGC 6341...      | −2.16 ± 0.02| 14.82 ± 0.16| 15.14 ± 0.1 | 15.21 ± 0.13 | 4.56 ± 0.15 | 19.38 ± 0.2 |
| NGC 6397...      | −1.76 ± 0.03| 12.24 ± 0.1 | 12.39 ± 0.1 | 12.39 ± 0.13 | 7.38 ± 0.15 | 19.62 ± 0.2 |
| NGC 7078...      | −2.02 ± 0.04| 15.30 ± 0.14| 15.62 ± 0.05| 15.67 ± 0.1 | 4.10 ± 0.12 | 19.40 ± 0.2 |

**TABLE 2**

Clusters and Parameters Used to Estimate the Distance

![Figure 7](image-url)

Fig. 7.—(B − R)_{R = −2.5}, the color of the RGB measured at M_R = −2.5, of Ursa Minor stars for elliptical annuli of increasing semimajor axis a.
duces an RGB compatible in color and wideness with Ursa Minor's.

The only remaining function to complete the SFH of Ursa Minor is the SFR, \( \psi(t) \). It has been solved for using the aforementioned partial-model method. To apply it, a single synthetic CMD is computed, embracing the full possible age interval (i.e., from 15 to 0 Gyr). This is divided into several partial models, each containing a stellar population with ages in a narrow interval. The Padua stellar evolution library (Bertelli et al. 1994) is used for this purpose. The basic idea is that any SFR can be simulated as a linear combination of partial models.

The solution for the SFR must have associated with it a CMD compatible with the observed one. To find such a solution, a number of boxes are defined in the CMDs (observed and partial models) and the numbers of stars inside them are counted. The boxes are defined in such a way that they sample stellar evolutionary phases, providing information about different ages. Let us call \( N_j^m \) the number of stars in box \( j \) in the observed CMD and \( N_j^{m_b} \) the number of stars in box \( j \) of partial model \( i \) (the partial model covering the \( i \)th age interval). Using this, the distribution of stars in boxes of an arbitrary SFR can be obtained from a linear combination of the \( N_j^{m_b} \), by

\[
N_j^m = k \sum_i \alpha_i N_j^{m_b} .
\]

The corresponding SFR can be written as

\[
\psi(t) = k \sum_i \alpha_i \Delta_i(t) ,
\]

where the \( \alpha_i \) are linear combination coefficients, \( k \) is a scaling constant, and \( \Delta_i(t) = 1 \) if \( t \) is inside the interval corresponding to partial model \( i \) and \( \Delta_i(t) = 0 \) otherwise. Finally, the \( \psi(t) \) having the best compatibility with the data can be obtained by a \( \chi^2 \) fitting of \( N_j^m \) to \( N_j^o \), the coefficients \( \alpha_i \) being the free parameters.

In practice, several choices of partial-model distributions were tried. However, choices involving time resolutions for old stars on the order of 1 Gyr fluctuate in a similar way to that shown by Olsen (1999), indicating that the data do not contain enough information for such small time sampling. On the other hand, the SFR at intermediate ages is so low (if any) that only an average estimate makes sense. In summary, after several trials, the adopted solution is based on a three partial model decomposition corresponding to the age intervals 2–10, 10–13, and 13–15 Gyr. The lower limit (2 Gyr) is the age of an isochrone having the turnover point at \( V \sim 1.5 \), corresponding to the upper point of the Ursa Minor blue plume (BP).

Moreover, 11 boxes have been defined in the CMD, as shown in Figure 8, to characterize the distribution of stars. Box 1 samples the old main-sequence (MS) population. Boxes 2–5 sample the BP population. In this analysis we will consider two possibilities in turn, namely, that all the BP stars are genuine MS stars (hence of intermediate age) and that all them are blue stragglers (hence old stars). We will discuss more about this in § 5. Boxes 6–8 cover the HB, while box 9 samples the region corresponding to intermediate-mass, core helium burning stars. Here we will assume that age is the only relevant second parameter to determine the HB morphology. However, it must be kept in mind that the nature of the second parameter is not fully confirmed and that the blueward extension of the HB depends on stellar evolution parameters that are not well controlled. This could affect the morphology of the SFR for the interval 10–15 Gyr, although the effects on the SFR integral for that period would be very limited.

Box 10 samples the RGB, populated by old and intermediate-age stars born in fact in the full, 2–15 Gyr interval considered here. For this reason, it gives no information on age resolution, but it provides a strong constraint to normalize the full SFR: independently of the age distribution, the integrated SFR for the old and intermediate-age stars must be compatible with it. Beside a few asymptotic giant branch (AGB) stars in the same age interval as the RGB stars, box 10 includes a number of foreground stars. This number is estimated from box 11 and simply subtracted from the counts in box 10.

The solution for the SFR is found in a global way, considering the number of stars in all boxes. In practice, it is not reasonable to look for the best solution (the linear coefficients best reproducing the distribution of stars in the boxes of the observational CMD), so we instead search all the solutions providing a stellar distribution compatible with the observed one within some interval. The criterion used here is to adopt as good all those solutions producing \( \chi^2 \) within \( \chi^2_{\nu, \text{best}} + 1 \).

The large spatial coverage of our data offers the opportunity to compare the stellar population in different regions of the galaxy. To do so, we have computed \( \psi(t) \) in the inner (\( a \leq 18' \)) and in the outer (\( 18' < a \leq 40' \)) regions defined in § 3. These values approximately correspond to the core and tidal radii (e.g., Irwin & Hatzidimitriou 1995 find \( r_c = 15'8 \) and \( r_t = 50'6 \), and Kley et al. 1998 obtain \( r_t = 34' \)). The results are shown in Figure 9. Error bars represent the dispersion of the accepted solutions.

As in the case of the Draco dSph galaxy (Aparicio et al. 2001), the solutions are very similar in both regions. However, a marginally significant difference could exist in the fraction of stars in the 10–13 Gyr interval relative to the 13–15 Gyr one, in the sense that the former could be relatively...
more frequent in the outer region of the galaxy. Since the difference is at the error-bar level, we do not discuss it further.

On the other hand, the solution is largely dominated by very old stars. Some 90% of the stars were formed in an initial, main burst lasting from 15 to 13 Gyr ago, and at least 95% of them were formed more than 10 Gyr ago. After that, two possibilities arise. If BP stars are normal MS stars, then star formation has gone on at a low rate until recent epochs. Alternatively, if BP stars are blue stragglers, then the star formation has been zero or negligible since 10 Gyr ago. For reasons discussed below (§ 5), we adopt the second possibility as the most reliable, which makes Ursa Minor the only Milky Way satellite lacking an intermediate-age stellar population.

The obtained SFR has been used to calculate the total mass in stars and stellar remnants (M\textsubscript{\text{ST}}) within 18' and within 40'. Both values are quoted in Table 3, and the second is used to calculate the dark matter fraction \( \kappa \).

The SFR has been also computed by Hernandez et al. (2000; see also Valls-Gabaud et al. 2000) for the central region of Ursa Minor using Hubble Space Telescope data. They obtained a solution qualitatively very similar to ours: a major star formation event at an early epoch forming all or almost all the stars in the galaxy. However, Hernández et al. (2000) find a maximum value of \( 6 \times 10^{-4} \, M_{\odot} \, \text{yr}^{-1} \) at about 14 Gyr and zero for ages less than 10 Gyr, while Valls-Gabaud et al. (2000) find \( 3 \times 10^{-4} \, M_{\odot} \, \text{yr}^{-1} \), also at ~14 Gyr. These authors calibrate their SFR scale by normalization to account for the total luminosity of Ursa Minor. To compare with them, we have to sum the solutions for our inner and outer regions. We obtain a maximum SFR of \( 2.7 \times 10^{-4} \, M_{\odot} \, \text{yr}^{-1} \) for the period 15–13 Gyr, quite similar to the Valls-Gabaud et al. (2000) value. It is important to stress the compatibility of both solutions, which is more noticeable considering the different approaches used by these authors and us.

### 5. The Nature of Blue Stars

To derive the SFH of Ursa Minor, we have considered in § 4 two possibilities about the nature of BP stars, namely, that they are normal, intermediate-age, MS stars or blue stragglers. Although it is probably impossible to conclusively ascertain which is the right possibility, a few tests can be made to check which of them is the more reliable. We will discuss in turn the following points, which should cast light on the problem: (1) the amount of stars in the red clump region of the CMD, (2) the relative number of BP stars, (3) their spatial distribution, and (4) the availability of gas in Ursa Minor.

#### 5.1. Stars in the Red Clump Region

If BP stars are genuine, intermediate-age, MS stars, they should have a counterpart in the red clump region of the CMD, sampled by box 9 (Fig. 8). However, this criterion is not sensitive enough: only two or three stars of this kind are expected to be found in this box, while some 20–22 old AGB stars evolving upward from the HB are expected to lie in the same box. This must be added to the fact that some foreground and background contamination is expected to affect this box, making the star counts in it more uncertain.

#### 5.2. Relative Number of Blue Stars

The number of blue stragglers relative to a reference population, namely, the HB stars, is used in the study of the frequency and distribution of blue stragglers in globular clusters and field stars. We have computed this number for Ursa Minor. Only the inner 18' has been used, to limit the effects of background and foreground contamination. The resulting number of blue stragglers relative to HB stars is \( F_{\text{BS}}^{\text{HB}} = 1.8 \). This can be compared with the results obtained for globular clusters by Piotto et al. (2002) and for Milky Way halo field, blue metal-poor stars (Preston & Sneden 2000). Piotto et al. obtain values in the range \( 0.1 \leq F_{\text{BS}}^{\text{HB}} \leq 1.0 \) for most globular clusters in their sample, larger values corresponding to less concentrated clusters. The only two exceptions have \( F_{\text{BS}}^{\text{HB}} \) between 2 and 3. Preston

### Table 3

**Morphological and Integrated Parameters of Ursa Minor**

| Parameter | Value | Ref. |
|-----------|-------|------|
| \( \alpha \) (J2000) | 250.092 | 1 |
| \( \delta \) (J2000) | 67.129 | 1 |
| \( \mu_{\alpha \cdot \gamma} \) | 25.5 ± 0.3 | 1 |
| \( r_c \) (arcmin) | 15.8 ± 1.2 | 1 |
| \( d \) (kpc) | 70 ± 4 | 2 |
| [Fe/H] | \(-1.9 ± 0.11\) | 3, 2 |
| \( V_T \) | 10.3 ± 0.4 | 4 |
| \( M_V \) | \(-8.9\) | 2 |
| \( L_V(L_c) \) | \(3 \times 10^5\) | 2 |
| \( M_{VT} (M_l) \) | \(23 \times 10^6\) | 2 |
| \( M_{VT} (M_l) / M_V \) | \(77\) | 2 |
| \( M_d (a < 18') (M_l) \) | \(2.25 \times 10^5\) | 2 |
| \( M_d (a < 40') (M_l) \) | \(3.6 \times 10^5\) | 2 |
| \( \kappa = 1 - [M_d (r < 40') / M_{VT}] \) | \(0.98\) | 2 |

Note.—Units of right ascension are hours and minutes, and units of declination are degrees and arcminutes.

References.—(1) Irwin & Hatzidimitriou 1995; (2) this paper; (3) Shetrone et al. 2001; (4) Caldwell et al. 1992.
& Sneden obtain $F_{\text{BS}}^{\text{HB}} = 4.4$. This scenario points to the blue stragglers possibly originating in close binary stars, which would be more efficiently destroyed in high-density globular clusters. This would account for the higher values of $F_{\text{BS}}^{\text{HB}}$ in lower density environments. Indeed, the value found here for Ursa Minor, which is intermediate between those of globular clusters and that of the Milky Way halo field, would be compatible with this scenario and would agree with the BP stars in Ursa Minor being blue stragglers.

5.3. Spatial Distribution of Blue Stars

A further test of the nature of the BP stars is based on their radial distribution. The gas coming from old, dying stars would have a radial distribution similar to that of these stars. But the fact that a critical density of gas is required to form new stars implies that these should preferentially form in the inner part of the galaxy (cf., e.g., the cases of NGC 185 and Phoenix in Martínez-Delgado et al. 1999a and 1999b, respectively). Figure 10 shows that the distribution of $F_{\text{BS}}^{\text{HB}}$ as a function of galactocentric distance in Ursa Minor is flat, indicating that the BP population is strongly related to the old stellar population and that it is very likely formed by blue stragglers.

5.4. Gas and Intermediate-Age Stars in Ursa Minor

Producing an intermediate-age population implies a mechanism to generate and conserve gas. Deep observations have failed to detect gas in Ursa Minor (Young 1999, 2000), even at large distances from the center of the galaxy (Blitz & Robishaw 2000). However, the gas could come, at a low rate, from early generation, dying stars. This could eventually allow small, short, and recursive star formation bursts that, smoothed and averaged, would account for a low rate of star formation at intermediate ages. The rate at which this material is returned to the ISM can be estimated from the integration of the SFR through

$$R(t) = \int_{m_i}^{m_u} [m - p(m)] \phi(m) \psi(t - \tau(m)) dm ,$$

where $m_i$ and $m_u$ are lower and upper integration limits for the stellar mass, $p(m)$ is the mass of the stellar remnant of a star of initial mass $m$, and $\tau(m)$ is the lifetime of a star of mass $m$. Note that we are using time increasing toward the past, with the present-day value being zero. We assume that all the gas returned to the interstellar medium from supernova (SN) explosions escapes the galaxy, and we will estimate only the gas coming from stellar winds of intermediate- and low-mass stars in the inner Ursa Minor region, where the density is higher. From a linear fit to Vassiliadis & Wood’s (1993) results for stars of metallicity $Z = 0.004$ (the lowest they compute) in the mass interval from 0.89 to 5.0 $M_\odot$, we obtain $p(m) = 0.489 + 0.093m_i$, where $m_i$ is the initial stellar mass. Using the SFR obtained in § 4 for the inner region ($a \leq 18'$) and for the case in which BP stars are assumed to be intermediate-age MS stars, the Kroupa et al. (1993) IMF, $m_i = 0.89$ $M_\odot$, and $m_u = 5.0$, we obtain an average $R(t) = 1.3 \times 10^{-5}$ $M_\odot$ yr$^{-1}$ for $2 \text{ Gyr} < t < 13$ Gyr (inner 18'). This value is 5 times the averaged SFR obtained in § 4 for that period, $\Psi_{13-2} = 2.5 \times 10^{-6}$ $M_\odot$ yr$^{-1}$.

However, in a dwarf galaxy such as Ursa Minor, gas is expected to be repeatedly removed through SN explosions. Van den Bergh & Tammann (1991) estimated that, for a galaxy of the luminosity of Ursa Minor, the SN Ia rate is one per 10$^7$ yr. In this interval, Ursa Minor (inner 18') would accumulate some 130 $M_\odot$ in all the gas from intermediate-mass (if any) and low-mass dying stars. Under these conditions, it seems very difficult to accumulate enough gas in any limited region of the galaxy to allow stars to form at intermediate ages.

To see this more clearly, it should be enough to consider that, if gas from intermediate- and low-mass dying stars were distributed across the galaxy as are the stars, the central gas density would reach a value of some $4.4 \times 10^{-3} M_\odot$ pc$^{-3}$ after 10 Gyr if not removed by SN explosions. This value corresponds to a particle density of $5 \times 10^{-3}$ cm$^{-3}$, much smaller than the values of about 1000 cm$^{-3}$ that are typical lower thresholds for star-forming regions (Shu, Adams, & Lizano 1987).

6. THE SFH SCENARIO IN URSA MINOR

In summary, the tests discussed in § 5 support the idea that BP stars in the Ursa Minor CMD are blue stragglers and that no significant intermediate-age stellar population is present in the galaxy. Consequently, the overall SFH for Ursa Minor can be sketched in the following way: In a first phase, lasting from about 15–13 Gyr ago with a further extension up to 10 Gyr ago, most or all the stars now populating the galaxy were formed. Unused gas would likely have been ejected or swept in the subsequent SN explosions. In a second phase, starting at the end of the first, dying stars injected gas into the interstellar medium. Some of it could have been used to form new stars, but, most likely, SN Ia explosions would have avoided the accumulation of enough gas at any moment of this phase, preventing any star formation at intermediate ages. In such a case, BP stars in Ursa Minor would be blue stragglers. The best solution for the SFH is shown by the solid line in Figure 9. Alternatively, the maximum SFR compatible with the BP stars’ being genuine, intermediate-age, MS stars is shown by a dotted line in the same figure.
It must be mentioned that in our analysis of Draco (Aparicio et al. 2001), we assumed that the BP was formed by genuine MS stars. The 2–3 Gyr old burst found in the SFH of Draco depends on this assumption, and for this reason, as quoted in Aparicio et al. (2001), the value found for of the SFR in that burst is to be considered an upper limit. But the burst also relies on the red clump and subgiant populations present in Draco’s CMD, for which the existence of an intermediate-age stellar population in Draco should be considered real. Summarizing, although apparently similar at first glance, Ursa Minor and Draco differ in two important properties: their dynamical structures, with Ursa Minor showing a tidal tail (Martinez-Delgado et al. 2001) but Draco lacking one (Aparicio et al. 2001), and Draco’s showing an intermediate-age stellar population, which is not present in Ursa Minor.

7. CONCLUSIONS

As a part of our project devoted to the study of the Ursa Minor dSph galaxy, the SFH of the galaxy has been presented. The analysis uses wide-field photometry, encompassing about $1^\circ \times 1^\circ$ (total covered area about 0.75 deg$^2$), and the synthetic CMD technique for the derivation of the SFH.

The resulting SFH shows that Ursa Minor hosts a predominantly old stellar population. Very likely, virtually all the stars were formed before 10 Gyr ago, and 90% of them were formed before 13 Gyr ago. This picture shows Ursa Minor as the Milky Way dSph satellite most resembling the original hypothesis of Baade, namely, that dSph galaxies were pure, old, globular-cluster–like systems. Nevertheless, Ursa Minor’s CMD shows a well-populated blue plume above the main, old, main-sequence turnoff. If these stars were genuine MS stars, Ursa Minor would have maintained a low star formation rate extending up to ~2 Gyr ago. However, (1) the relative number of BP stars to HB stars, (2) the spatial distribution of BP stars, and (3) the gas availability argue against this possibility and strongly favor the BP stars being a blue straggler population. In this context, Ursa Minor would remain the only dSph Milky Way satellite hosting a pure old stellar population.

The SFH study was performed for two regions of the galaxy, namely, that within the core radius and that between this and the tidal radius. No significant differences were found between the stellar populations in both regions, except for the fact that the fraction of stars found in the 10–13 Gyr interval is marginally larger.

Besides the SFH analysis, the distance of Ursa Minor has also been derived from a comparison of the galaxy HB magnitude with those of some globular clusters. These were chosen to have the same metallicity and HB morphology as the galaxy. We obtained a distance of $76 \pm 4$ kpc. The metallicity was also estimated from the RGB color to be $[\text{Fe}/\text{H}] = -1.9 \pm 0.25$, in agreement with the spectroscopic value by Shetrone et al. (2001). No metallicity gradient is detected along the galaxy.

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