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A bright early-type star in the halo of NGC 253: Runaway or in situ formation?⋆

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Abstract. We present observations of J004804.8-251749, a blue object in the direction of the halo of NGC 253 with $(B - V) = -0.16 \pm 0.08$, $V = 22.09 \pm 0.06$ and a stellar spectrum showing the Balmer lines redshifted to a velocity of 279 ± 15 km s^{-1}. These data are consistent with a B5/B8 supergiant star with a mass $M = 12$ $M_\odot$ and a maximum age $\tau \simeq 20$ Myr in the halo of NGC 253. Based on its position, radial velocity, and inferred maximum age, we consider the possibility that J004804.8-251749 may be a runaway star ejected from the disk of NGC 253. We derive a lower limit of 172 km s^{-1} for the ejection velocity, or 148 km s^{-1} if the lower limit of the distance fork to NGC 253 is adopted. While being within the range of velocities accessible to runaway stars through the dynamical ejection mechanism, such high velocities are rather unlikely, especially since the inferred value is only a lower limit. This leads us to consider in situ formation as a possible alternative scenario, in which the formation of J004804.8-251749 would have been triggered by the interaction between the starburst-driven superwind stemming from the center of NGC 253 and a cloud of cold hydrogen in the halo. Such a formation mechanism would be consistent with our previous finding of an excess of blue point sources in the direction of the halo of NGC 253, which we interpreted as indicating the existence of superwind-triggered star formation.

Key words. stars: early-type – stars: formation – stars: kinematics – galaxies: starburst – galaxies: individual: NGC 253

1. Introduction

In an effort to explore the possible existence of star formation in the haloes of galaxies with central starbursts, Comerón et al. (2001) (hereafter CTMG) recently presented statistical indications of an excess of blue sources in the direction of the halo of NGC 253. This galaxy is a nearly edge-on spiral in the Sculptor Group with a superwind powered by its central starburst (Lehnert & Heckman 1996; Strickland et al. 2000; Pietsch et al. 2000). The excess of sources with $B - V < 0$ seen in the direction of the halo of this galaxy as compared to two nearby control fields extends to projected distances of up to 15 kpc from its midplane. This is very difficult to explain if these objects are stars initially formed in the disk and then expelled to the halo by one of the two mechanisms proposed to explain the existence of runaway stars, namely dynamical ejection or supernova explosion of a massive companion (Poveda et al. 1967; Blaauw 1961). CTMG suggested that at least part of these blue sources could be early-type stars formed in situ, perhaps as a result of the interaction of the hot superwind gas with warm neutral clouds similar to the high-velocity clouds (HVCs) observed in the halo of the Milky Way (Wakker & van Woerden 1997; Wakker et al. 1999). Despite of the statistical significance of the excess of blue sources, it is not possible from the observations presented by CTMG to ascertain with certitude which of the objects observed may actually be early-type stars. On the one hand, a certain level of contamination by QSOs and AGNs having similar colors is expected to be present in the observed fields. On the other hand, the faint objects among which such excess is detectable have relatively large photometric uncertainties and some of them may actually be somewhat redder, but moved by photometric errors to the $B - V < 0$ region. As noted by CTMG, the characterization of the population of blue objects needs their spectroscopic confirmation.

This spectroscopic follow-up program is being carried out at present by us at the ESO Very Large Telescope (VLT), and a full presentation of the results is planned once the full set of observations is completed. However, existing data have allowed us to confirm already the stellar nature of one of the blue objects. The spectroscopic, photometric, and positional data available allow us to derive data concerning its physical properties

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⋆ Based on observations obtained at the European Southern Observatory using the Very Large Telescope in Cerro Paranal (programme 69.D-0109(A)).

and evolutionary status, as well as to place some constraints on its origin that are discussed in this paper.

2. Observations

The observations presented here were carried out on the nights of 7 and 8 September 2002 using FORS1, the visible-light imager and low resolution spectrograph at the VLT. Images of six overlapping fields covering an area of $13.4' \times 20.1'$ along the Southern extension of the minor axis of the galaxy's image were obtained through the B and V filters at the beginning of the night of 7 September, for a total exposure time of 16 min per field and filter. The purpose of these images was to provide the preimaging needed for the accurate positioning of the slits in the ensuing multiobject spectroscopy (MOS), as well as to allow more accurate BV photometry than possible from the already existing NTT images used by CTMG thanks to the greater depth of the VLT images even with such moderate exposure times. On-site reduction and photometry of the images using dedicated IRAF-based scripts and the photometric sequence of Alcaino & Liller (1984) enabled us to quickly identify objects of interest for follow-up based on their blue $B - V$ color and their point-like appearance. The movable-blades facility of FORS1, which allows the quick definition of MOS masks, made it possible to prepare the MOS observations of the potentially interesting objects in each observed field while the rest of the fields were still being imaged. In this way, we could immediately proceed with the MOS observations of the first field as soon as the last images were obtained.

The MOS observations were performed during the rest of our observing run. We used a grism providing a dispersion of 2.7 Å pix^{-1} resulting in a resolution $R = 300$ with the $1''$-wide slits used. Observations in each MOS setting consisted of a number of 30-min exposures with small telescope offsets along the slits between each consecutive pair of exposures. In the case of the setting containing the object described in this paper the total exposure time is 2.5 hours. Spectra of each object were extracted from each individual bias-subtracted, flat-fielded frame. Wavelength calibration was performed using an exposure of a HeAr lamp obtained at the end of each night through the same MOS mask. The individual spectra extracted for each object were then coadded and the result was calibrated in relative flux using an observation of the spectrophotometric standard LDS749B obtained with the same grism.

3. Results

The available observing time in our September 2002 run allowed us to obtain MOS for only three of the six targeted fields. The spectra of blue objects that we obtained can be divided in two broad classes depending on the presence or absence of emission lines. Objects with emission lines are AGNs and QSOs at various redshifts, which can usually be determined when two or more lines are visible, and therefore are not of interest for the purpose of this work. On the other hand, the nature of most of the objects without emission lines is still unclear, as the signal-to-noise ratio is generally insufficient for the identification of absorption lines. These objects thus retain their status as possible NGC 253 halo stars, which will need to be confirmed by deeper spectroscopy in the future.

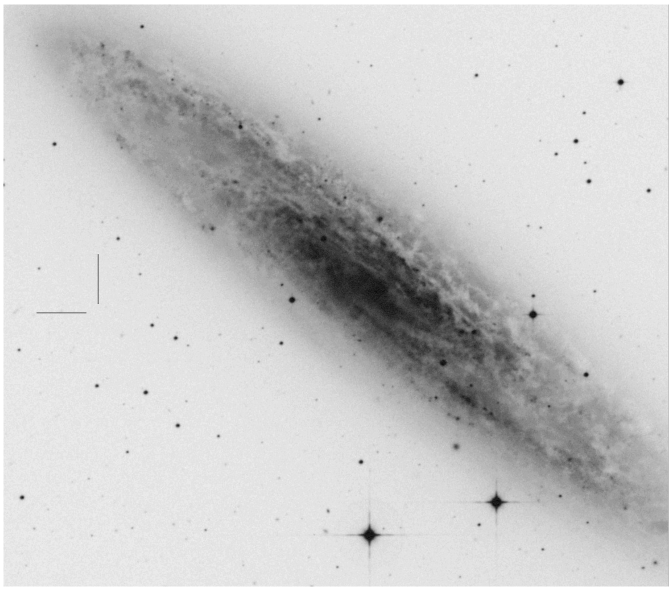

Fig. 1. A Digitized Sky Survey image of the field around NGC 253, with the position of J004804.8-251749 (too faint to be seen in this image) indicated.

The exception to the latter class is an object located at $\alpha(2000) = 0^{\rm h}48^{\rm m}04\overset{\rm s}{.}8$, $\delta(2000) = -25°17'49''$ that is among the brightest ones that we observed, having $V = 22.09 \pm 0.06$, $B - V = -0.16 \pm 0.08$. The location of the object, hereafter referred to as J004804.8-251749, or J004804.8-251749 for short, with respect to the galaxy is indicated in Fig. 1, and Fig. 2 shows a close-up view from the B-band image. Its spectrum, shown in Fig. 3, clearly shows the Balmer and CaII K lines near their rest wavelengths. A measurement of their wavelengths translates into a radial velocity $v_* = (279 \pm 15)$ km s^{-1}, comparable to the overall recession velocity of 251 km s^{-1} of NGC 253 (Puche et al. 1991).

It is extremely unlikely that this object belongs to the halo of our own Galaxy. The comparable strength of the H and CaII K lines in the blue rules out a DZ white dwarf or a sdB subdwarf as a possible explanation (Wesemael et al. 1993; Munari & Zwitter 1998; Theissen et al. 1993), while a normal, main sequence mid B-type star with this magnitude would require a distance modulus $DM \simeq 23.3$, well into intergalactic space. If it were a blue post-AGB star the distance modulus would increase to $DM \simeq 25.2$, even farther than in the case of a main sequence B star but clearly insufficient to place it at the distance of NGC 253.

We thus consider that J004804.8-251749 most likely belongs to the halo of NGC 253. Adopting a distance of 2.6 Mpc for NGC 253 ($DM = 27.06$; Puche & Carignan 1988), the absolute magnitude is $M_V = -4.96$, suggesting that it could be either a late O-type star or a later-type giant/supergiant. The first possibility can be ruled out in view of the color index, which is over 0.1 mag redder than that of a normal O-type star. We do not consider that interstellar reddening has a significant contribution in this case, since the line of sight does not

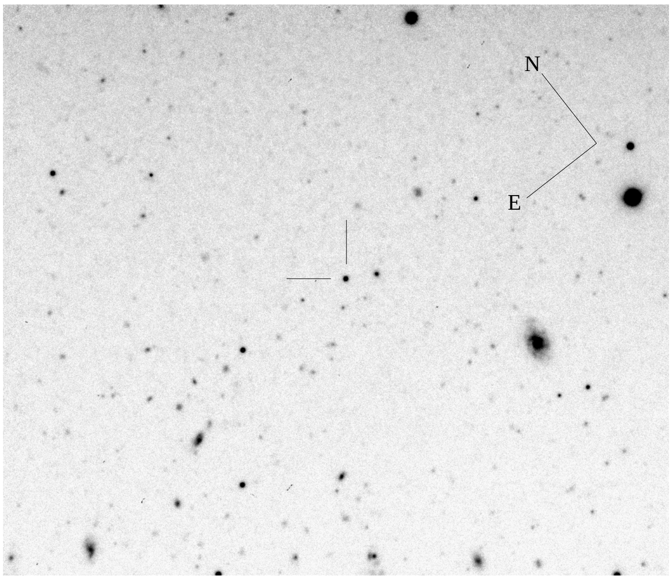

Fig. 2. A finding chart for J004804.8-251749 in the B band, indicated in the figure. The horizontal direction is parallel to the major axis of NGC 253 on the sky. J004804.8-251749 is located at $\alpha(2000) = 0^{\rm h}48^{\rm m}04\overset{\rm s}{.}8$, $\delta(2000) = -25°17'49''$ and the size of the field of view shown here is $3\overset{'}{.}17 \times 2\overset{'}{.}71$.

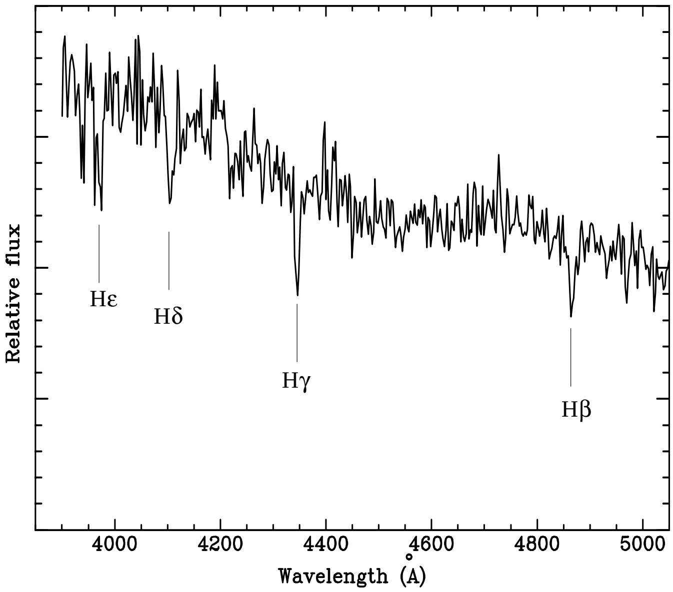

Fig. 3. The coadded spectrum of J004804.8-251749, with the Balmer lines indicated. The only other line seen is the CaII K line, consistent with the mid B-type classification proposed here.

intersect the disk of NGC 253 and the local extinction by dust in the Milky Way disk is very small ($A_V = 0.03$; Tully 1988) in this direction, nearly perpendicular to the galactic plane. The signal-to-noise ratio of our spectrum is not sufficient to reveal lines of helium, either neutral or ionized, which should however be visible if the star were a late-O or early-B. The lack of prominence of any lines other than those of the Balmer series and the CaII K line in our spectrum is consistent with a spectral type between mid-B and mid-F (see e.g. the comprehensive atlas of low-resolution spectra of Jacoby et al. 1984), but the blue color rules out a type later than about B8. This is also consistent with the absolute magnitude derived above, according to the calibration of Humphreys & McElroy (1984), if J004804.8-251749 has a Ib-II luminosity class. We thus consider J004804.8-251749 as a mid B-type supergiant. A comparison of the spectrum of J004804.8-251749 with the atlas of B-type stars in NGC 300 of Bresolin et al. (2002), obtained with the same instrument in a similar setup but at a higher signal-to-noise ratio thanks to the higher brightness of those objects, is also in agreement with this classification.

3.1. Physical properties and evolutionary status

The bolometric luminosity and effective temperature of J004804.8-251749 can be inferred by adopting the relationships between temperature, color, and bolometric correction of Castelli (1999). We obtain $L = 2.6 \times 10^4\ L_\odot$, $T_{\rm eff} = 15\,000$ K, consistent with the spectral type adopted in the previous Section. Both derived quantities are somewhat uncertain mainly due to the rather limited accuracy of the $(B-V)$ color; surface gravity and metallicity have a much smaller effect on the uncertainty on the temperature, which we estimate to be $\simeq 3\,000$ K. The lower end of the uncertainty range is given by the color, whose dependence with temperature becomes steeper at lower temperatures. In the other end, a temperature higher than $\simeq 18\,000$ K would imply an early B-type spectrum with helium lines that should be visible in Fig. 3. The uncertainty in the luminosity arises from the uncertainty in the photometry (0.06 mag), in the distance modulus (0.6 mag as given by Puche & Carignan 1988; see discussion in Sect. 4) and in the bolometric correction, that we take as 0.4 mag from the uncertainty in $B-V$ and the color-bolometric luminosity relationship. Taking all these factors together, we estimate $\Delta \log L = 0.4$. The conclusions regarding the possible nature and evolutionary status of J004804.8-251749 are essentially unaffected by these uncertainties, as we discuss below.

A comparison of the derived temperature and luminosity with the models of high-mass evolution of Meynet & Maeder (2000) indicates that J004804.8-251749 is an evolved star with an initial mass of 12 $M_\odot$. The inferred age depends on the adopted initial rotation velocity and the metallicity. The hydrogen-burning phase of a solar metallicity, rapidly rotating star of that mass lasts for 16.8 Myr, while models incorporating rotation indicate that the helium-burning phase takes place entirely when the star has already become a red supergiant. However, rotation also produces a "blue loop" in the evolution of solar metallicity stars with initial masses below 15 $M_\odot$ during the helium-burning phase that may reproduce $B-V$ colors and an absolute magnitude similar to the observed ones. The end of the helium-burning phase for a rapidly rotating star with solar metallicity thus sets and absolute upper limit to the age of J004804.8-251749 of 19.3 Myr. The assumption of a solar initial composition is very doubtful in view of the location and uncertain origin (see Sect. 4) of this object, and much higher quality spectra would be needed to assess the metallicity (Lennon 1997). The impact of the initial composition on the duration of the different evolutionary stages is nevertheless moderate, with the increases in the initial He yield and the metallicity each changing the H- and He-burning lifetime in opposite directions (Bono et al. 2000). Taking all these possibilities into account, we estimate rather conservatively an upper limit of 20 Myr for the age of J004804.8-251749.

4. Position, kinematics, and possible birthplace

The location of J004804.8-251749, its measured radial velocity and the upper limit to its age discussed in Sect. 3.1, and the rotation curve of NGC 253 allow us to consider in some detail the possibility that J004804.8-251749 might have been ejected from the disk of NGC 253 as a runaway star. On the basis of the ejection velocity required by this mechanism in order to account for the currently observed position and radial velocity of J004804.8-251749 we can then assess the plausibility of such an explanation versus the alternative of an in situ formation.

Let us consider for this purpose a Cartesian coordinate system having its origin at the center of NGC 253. The axes are defined such that x is directed along the line of sight and is positive in the direction toward us; y is coincident with the major axis of the oval of NGC 253 projected on the sky, being positive towards the southwest in Fig. 1; and z is coincident with its minor axis, being positive towards the northwest. In this coordinate system and assuming that the distance to NGC 253 is known, we can easily determine y and z by simply measuring the position of J004804.8-251749, while x is unknown. Let us now consider another coordinate system with the same origin but now with x' being the projection of x on the plane of the galaxy, z' being perpendicular to the plane of the galaxy, and y' being perpendicular to both and coincident with y as defined before. The transformation between both systems is

$$\begin{aligned} x' &= x \sin i - z \cos i & \text{(1a)} \\ y' &= y & \text{(1b)} \\ z' &= x \cos i + z \sin i & \text{(1c)} \end{aligned}$$

where i is the angle between the x' axis and the plane of the sky. In principle i can be easily measured from the projected shape of the galaxy as either 78° or 102°, depending on which edge of the projected oval of NGC 253 is closest to us. This uncertainty can be resolved by carefully examining the structure of the disk in images such as those published by Sofue et al. (1994) or Lehnert & Heckman (1996) in order to find foreground structures blocking the light from their background. This is also possible from the DSS image, where a lane of dark clouds is apparent along the northwestern rim that is absent in the southeastern one. This shows that the northeastern rim is foreground to most of the galaxy and thus that the visible disk of NGC 253 is the hemisphere facing southeastwards, implying that $i = 102°$.

A similar transformation applies to the components of the velocity along these axes:

$$\begin{aligned} v_{x'} &= v_x \sin i - v_z \cos i & \text{(2a)} \\ v_{y'} &= v_y & \text{(2b)} \\ v_{z'} &= v_x \cos i + v_z \sin i & \text{(2c)} \end{aligned}$$

where v_x is the difference between the bulk velocity of NGC 253 (Sect. 3) and the observed radial velocity of J004804.8-251749, v_* (also indicated in Sect. 3). In view of our choice of the sign of x, $v_x = -28$ km s^{-1}. The v_y component is totally unknown, while the $v_{z'}$ component can be estimated assuming that J004804.8-251749 formed in the plane of NGC 253. Assuming that the gravitational potential Φ of NGC 253 can be expressed as $\Phi(R, z') = \Phi_R(R) + \Phi_{z'}(z')$, where $R = \sqrt{x'^2 + y'^2}$,

$$v_{z'}(z') = v_{z'}(z' = 0) - \int_{\xi=0}^{z'} \frac{\mathrm{d}\Phi_{z'}(\xi)}{v_{z'}(\xi)} \cdot \quad (3)$$

The evaluation of the integral in Eq. (3) requires in principle the knowledge of the potential of the galaxy perpendicular to the disk. However, we can expect that for large components of the ejection velocity perpendicular to the plane of the galaxy the second term in the right-hand side of Eq. (3) be small as compared to the first term, and may thus be neglected. We must indeed expect a large value of the vertical component of the ejection velocity on the basis of the small value of the age of J004804.8-251749 discussed in Sect. 3.1, which thus allow us to approximate $v_{z'}$ as

$$v_{z'} \simeq \frac{z'}{\tau} \quad (4)$$

where τ is the age of J004804.8-251749. Being itself an uncertain quantity (Sect. 3.1), we can consider that the uncertainty in τ engulfs the smaller effect of the neglection of the deceleration due to the gravitational force perpendicular to the galactic disk. Under this approximation,

$$v_z = \frac{x/\tan i + z}{\tau} - \frac{v_x}{\tan i} \cdot \quad (5)$$

If we assume arbitrary values for the unknown quantities x and v_y we can integrate the equations of motion backwards to find the birthplace of J004804.8-251749 and the velocity with which it was ejected:

$$\begin{aligned} \frac{\mathrm{d}v_{x'}}{\mathrm{d}t} &= -\frac{V^2}{R^2} x' & \text{(6a)} \\ \frac{\mathrm{d}v_{y'}}{\mathrm{d}t} &= -\frac{V^2}{R^2} y' & \text{(6b)} \end{aligned}$$

where the force per unit mass is derived by equating it to the centrifugal force per unit mass at radius R. The rotation curve of the galaxy has been published by Puche et al. (1991) and can be approximated by

$$V(R) \simeq 35 + \frac{85.83}{f} R - \frac{16.25}{f^2} R^2 + \frac{1.04}{f^3} R^3 \quad (7)$$

with $V(R)$ expressed in km s^{-1} and R in kpc. The scaling factor $f = D/(2.6$ Mpc) allows for the use of a distance D to the galaxy different from the 2.6 Mpc assumed by Puche et al.

After integrating backwards the trajectory of J004804.8-251749 for a length of time equal to its age, we can calculate the velocity with which it was ejected by computing the difference between its velocity at birth and that of a star at the same location moving in a circular orbit around the center of the galaxy:

$$v_{\rm ej} = \sqrt{\left(v_{x'0} + V\frac{y'}{R}\right)^2 + \left(v_{y'0} - V\frac{x'}{R}\right)^2 + v_{z'}^2} \tag{8}$$

where $v_{x'0} = v_{x'}(t = -\tau)$, $v_{y'0} = v_{y'}(t = -\tau)$, $V = V(R)$.

The precise value of $v_{\rm ej}$ is obviously unknown, as it depends on the values adopted for x and v_y. However, it is possible to determine the values of those two free parameters that minimize $v_{\rm ej}$. Two local minima are found, one for the far side of the galaxy ($x < 0$, $v_y < 0$) and another for the near side ($x > 0, v_y > 0$). The value at the far side minimum is the lowest and indicates an ejection velocity of 172 km s^{-1}, with the star at $x = -8.0$ kpc and a present velocity along the major axis $v_y = -244$ km s^{-1}. At that position the distance perpendicular to the plane is $z' = -1.86$ kpc. The derived position of the birthplace is at $R = 9.3$ kpc from the center of the galaxy, somewhat past the edge of the disk visible in Fig. 1 but still within the R_{25} contour and the HI disk, which extend respectively to 10.4 kpc and 12.5 kpc (Puche et al. 1991; it may be interesting to note that ionized gas is detected up to a galactocentric distance of 15 kpc, according to Bland-Hawthorn et al. 1997).

This estimate does not take into account the uncertainty in the distance modulus of NGC 253, which amounts to ΔDM = 0.6 mag (Puche & Carignan 1988) corresponding to a lower limit to the distance of 2.0 Mpc. A distance somewhat shorter than the one adopted here is indeed suggested by Davidge & Pritchet (1990) who, based on the magnitudes of red giants detected in its halo, derive an upper limit of $DM = 26.8$ mag for NGC 253. Assuming a smaller distance decreases the lower limit derived above not only by reducing the geometric distance travelled by the star, but also by implying a lower luminosity and hence a lower mass and a longer H-burning phase. The reduction of 0.24 dex in $\log L$ caused by a decrease of 0.6 mag in the distance modulus, which is at the edge of the uncertainty given by Puche & Carignan (1988), places J004804.8-251749 near the 10 $M_\odot$ evolutionary track for a rapidly rotating star of solar metallicity, whose H-burning stage extends for $\simeq$25 Myr. Since the edge of the blue loop in the He-burning stage does not reach the high temperatures needed to account for the blue color observed in J004804.8-251749 in the case of a 10 $M_\odot$ progenitor, we take in this case the end of the H-burning phase as the upper limit to the age of J004804.8-251749.

Repeating the calculations outlined above now assuming a distance of 2.0 Mpc, we obtain a minimum of the ejection velocity at $v_{\rm ej} = 148$ km s^{-1}, with the star located at $x = -5.6$ kpc, $z' = -1.54$ kpc and moving with a velocity along the major axis $v_y = -214$ km s^{-1}. The birthplace is estimated to be at $R = 6.6$ kpc, which like in the previous case is near the edge of the visible disk when taking into account the reduced dimensions of the galaxy when a nearer distance is assumed.

5. Discussion: The origin of J004804.8-251749

In Sect. 4 we have shown that a minimum ejection velocity of 148 km s^{-1} is needed to be consistent with the position and radial velocity of J004804.8-251749 as observed at present. It must be stressed that this is a lower limit requiring the concurrence of a number of unrelated factors: a distance to NGC 253 at the nearest value allowed by the observations, an age of J004804.8-251749 near the end of its H-burning phase and, especially, a precise value of the position of the star along the line of sight and of the component of its velocity in the plane of the sky parallel to the major axis.

Even assuming that the ejection velocity of J004804.8-251749 was near that lower limit, its value is still very high for a runaway star, although not impossible. Hoogerwerf et al. (2001) have listed 56 O-B5 stars from the *Hipparcos* catalog with measured space velocities, only four of which exceed 148 km s^{-1} and two of which exceed the 172 km s^{-1} that we derive if NGC 253 is at a distance of 2.6 Mpc. Considerably higher runaway velocities seem to be possible though, as demonstrated by the case of HIP 60350, a 5 $M_\odot$ B4/B5V star moving with a velocity of 417 km s^{-1} (Maitzen et al. 1998; Tenjes et al. 2001). The dynamical ejection scenario seems favored as a mechanism to produce such extreme velocity runaways, as binary-binary encounters in dense groups seem indeed able to produce the ejection of the lowest mass members of the group with velocities comparable or even higher than the highest actually observed (Leonard 1991, 1995). Nevertheless, in the case of J004804.8-251749 such a mechanism would involve a close binary-binary encounter in which the other three stars involved should have masses high above 12 $M_\odot$, which should be a unusually rare event. On the other hand, although both of the proposed scenarios normally produce runaway stars with velocities well below the lower limit derived for J004804.8-251749, the binary supernova scenario seems especially disfavored in this case. First, the high velocity required is extremely unlikely to be produced in the disruption of a binary supernova (Portegies-Zwart 2000), as the probability of an ejection velocity above 150 km s^{-1} for a 10 $M_\odot$ star is below 1%. Secondly, the high orbital speeds needed could be reached only in close binary systems undergoing mass transfer between their components, resulting in a He-enriched companion (e.g. Blaauw 1993; Vanbeveren et al. 1998). The absence of discernible He lines in the spectrum of J004804.8-251749 (Fig. 3) seems to argue against this being the case, although clearly higher quality spectra would be needed to confirm this. In summary, the runaway origin scenario of J004804.8-251749 (probably via dynamical ejection) is not ruled out by the available data. However, its viability requires a rather specific choice of two parameters that are unconstrained by the observations, and is made even more unlikely if the distance of NGC 253 is the commonly adopted value of 2.6 Mpc rather than the lowest value allowed by the observations of 2.0 Mpc.

Given the difficulties of the runaway ejection scenarios, the in situ formation hypothesis becomes an interesting alternative. Both Hα images (Lehnert & Heckman 1996 and recent *Chandra* X-ray observations (Strickland et al. 2000) clearly show the origin of the outfow at the center of NGC 253 as a cone with 26° aperture extending to the southeast. Wider-area images at lower resolution obtained by *ROSAT* in the soft X-ray bands (Pietsch et al. 2000) show an extended, broader, roughly crescent-shaped structure with its axis in the same direction and a wider opening angle, of approximately $\theta \simeq 60°$. The position of J004804.8-251749 is superimposed on the eastern horn of the crescent. Rough estimates of the outflow parameters suggest an outflow rate of the order of $\dot{M}_w \sim 1\ M_\odot\ \mathrm{yr}^{-1}$ with a velocity of $v_w \sim 3000$ km s^{-1} at the base of the outflow (Strickland et al. 2000) which, neglecting mass loading, implies a particle density of $n_\mathrm{H} \simeq (0.5\ \dot{M}_w)/[1.4\pi h^2 v_w m_\mathrm{H} \tan^2(\theta/2)]$, or $n_\mathrm{H} \simeq 4.5 \times 10^{-3}\ \mathrm{cm}^{-3}/h^2[\mathrm{kpc}]$ at a height h over the disk of the galaxy. Assuming that J004804.8-251749 lies near the plane perpendicular to the line of sight containing the center of NGC 253, $h \simeq 3.5$ kpc and $n_\mathrm{H} \simeq 3.7 \times 10^{-4}$ cm^{-3}. The superwind may thus be expected to be a high velocity stream of considerably high density, able to induce important hydrodynamical effects on any denser clouds encountered along its path. This scenario bears some resemblance with the interaction of supernovae or stellar wind-blown bubbles with interstellar clouds, which has been studied by a number of authors (see e.g. Oettl et al. 1985; Różyczka & Tenorio-Tagle 1987; Stone & Norman 1992; Klein et al. 1994; Foster & Boss 1996 for a wide variety of results corresponding to different scales and initial conditions). The outcome of the interaction can be either the disruption of the cloud or its externally induced gravitational collapse, depending greatly on the physical conditions of the cloud and the parameters of the interaction. The latter possibility may provide an explanation for the origin of J004804.8-251749 and other similar objects that may be present in the halo of NGC 253, and might also account for the existence of objects such as the isolated HII region near NGC 4388, a Seyfert galaxy in the Virgo cluster, recently reported by Gerhard et al. (2002). Unfortunately, the existing observations can do little to constraint the initial parameters of the hypothetical clouds leading to the formation of J004804.8-251749-like objects in NGC 253, and it is not possible to ascertain the degree of likelihood of this scenario. Numerical simulations of the dynamical evolution of thermally unstable condensations or of mass loading in starburst superwinds might allow an assessment of whether or not the mechanism just outlined is a more plausible one than the runaway origin for J004804.8-251749.

6. Conclusions

This paper has reported on the discovery of J004804.8-251749, a $V = 22.09$ B-type supergiant in the lower halo of NGC 253. Comparison to evolutionary models indicate a mass of 12 $M_\odot$ and an age of 20 Myr, and its radial velocity is $v_* = (279 \pm 15)$ km s^{-1}, similar to the recession velocity of NGC 253. Based on the positional, kinematic, and evolutionary information available we have considered the possibility that J004804.8-251749 may be a runaway star formed in the disk of the galaxy and subsequently ejected into the halo. We are able to estimate a minimum ejection velocity of 172 km s^{-1}, which reduces to 148 km s^{-1} if the minimum distance to NGC 253 consistent with the observations is assumed. This velocity is not incompatible with a runaway origin, most probably by dynamical ejection in a compact cluster, but it is highly unlikely and moreover it is only a lower limit. We have qualitatively discussed the alternative possibility of J004804.8-251749 having formed in situ as a consequence of the interaction of the superwind caused by the central starburst of NGC 253 with cold gas in the halo. J004804.8-251749 is located near the edge of the outflow cone traced by extended X-ray emission, at a distance from the galaxy where the density of the high velocity superwind with possible clouds of neutral gas may have important dynamical consequences on the latter. We thus consider that this second scenario is a plausible alternative to the highly unlikely constraints set by observations on the runaway ejection scenario.

How can we discern between both possibilities? It is unlikely that new observations of J004804.8-251749 in the near future may yield much more information on its physical characteristics. A spectrum of sufficient quality to allow the determination of chemical abundances, for instance, is a challenging task with present day instrumentation even on a 8m-class telescope, while the 244 km s^{-1} transverse velocity predicted by the runaway scenario translates to a 2 μas yr^{-1} proper motion, undetectable even with GAIA for such a faint object.

It may be easy however to perform a simpler observation that may prove the in situ formation scenario. If J004804.8-251749 was formed by the compression of a cloud in the halo of NGC 253 it is rather unlikely that such event would have formed a single massive star. A deep search in a region around J004804.8-251749 may thus reveal other possibly less massive stars formed at the same time as J004804.8-251749, which would not be the case if J004804.8-251749 had a runaway origin. On the other hand, the indications found by CTMG that other blue stars may exist at greater distances from the disk, if spectroscopically confirmed, would make the runaway ejection scenario even more unlikely. While our observations do not prove that starburst-triggered star formation exists in the halo of NGC 253, the discovery of a young massive star at such an unusual location provides a strong incentive to pursue the search for such evidence.

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