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Stellar tracers of the Cygnus Arm

I. Spectroscopic study of bright photometric candidates*

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Abstract. We present medium-resolution spectroscopy of a sample of stars in the second Galactic quadrant selected from the literature because their colours suggest that they are moderately-reddened early-type stars at very large distances. From the derived spectral types and observed colours, we calculate distances to all these objects. For a sizable fraction of our sample, we find distances well in excess of what is expected for Perseus Arm objects, even allowing for rather generous errors. In the interval $l = 150°-180°$, there is a large number of objects with distances in excess of 4 kpc, which are likely tracing the Outer or Cygnus Arm. In particular, we find that the association Cam OB3 is placed on this Arm. Based on our results, the extent and definition of the associations Cas OB4 and Aur OB2 need to be reevaluated.

Key words. stars: early-type – stars: distances – Galaxy: structure – open clusters and associations: general

1. Introduction

Since they are necessarily young, OB stars – in particular, those clearly belonging to an association or illuminating an H II region – trace the areas of recent star formation. As star formation happens preferentially in the spiral Galactic arms, it has been generally considered that O and early-B type stars can be used as spiral-structure tracers, at least when they are studied in relatively large numbers (cf. Russeil 2003). After all, the first conclusive evidence for the spiral structure of the Milky Way was derived from the distribution of OB associations in the Solar neighbourhood (Morgan et al. 1952).

In spite of several earlier efforts (e.g., Isserstedt 1970; Moffat & Vogt 1973), an outline of the Galactic spiral structure based on optical tracers was only achieved by Georgelin & Georgelin (1976), based fundamentally on data from H II regions and their exciting stars. Their sketch of Galactic structure included four spiral arms, with the Sun being located in a minor feature or spur, generally known as the Orion Spur. The main spiral structure is determined by the Sagittarius-Carina Arm (i.e., the first arm towards the Galactic Centre from the position of the Sun or −I arm) and the Norma (−III or internal) Arm. The two other arms, Perseus (the first arm towards the outside from the position of the Sun or +I arm) and Scutum-Crux (−II) were suspected to be less important features.

The picture of the Galaxy today is more elaborate, including a bar and a central ring (e.g., Vallée 2002), as well as a warp in the outer regions (e.g., Drimmel & Spergel 2001), but the basic design still survives. Though Fernández et al. (2001) conclude that a two-arm model cannot be ruled out with existing observations, most modern studies favour a four-armed Galaxy (Vallée 2002; Russeil 2003).

Already at the time when the first basic picture appeared, it was noted that several young star clusters in the Anticentre direction were located at heliocentric distances of 5–6 kpc (Moffat & Vogt 1975), far beyond the expected position of the Perseus Arm, and it was suspected that they were tracers of a more external (+II) arm. More recent work has confirmed the long distances to clusters such as Bochum 2 (Munari & Carraro 1995) or Dolidze 25 (Lennon et al. 1990) – both at ($l \approx 212°$). In addition, Turbide & Moffat (1993) found 6 other young star groupings associated to H II regions in this area, lying at distances in the 5–9 kpc range. Recent distance determinations indicate that the much larger open cluster NGC 1893 ($l = 173.6°$), previously believed to be the core of the Aur OB2 association, is also located at a heliocentric distance of ∼6 kpc (Marco et al. 2001), suggesting that this star-forming region also belongs to the Outer Arm.

Molecular clouds definitely delineating an Outer Arm are readily visible in CO surveys all over the first Galactic quadrant, where they display radial velocities clearly distinct from those of Perseus Arm clouds (Dame et al. 2001). This Outer Arm, the first spiral arm encountered beyond the Perseus Arm, is generally referred to as the Cygnus Arm. In most models,

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Table 1. Distant OB stars observed from the OHP 1.52-m telescope. The first column indicates the volume and number in the Luminous Stars catalogue. The fourth and fifth columns indicate the dates when the two spectral positions were observed and (between brackets) the exposure time in seconds. The derived spectral types are given in the sixth column. Spectral types marked with a "*" are less secure than the average, because of poor signal to noise, presence of double lines or absence of one of the two spectral regions. Stars whose spectral types are given as "(−)" were re-observed with the 1.93-m telescope and their spectral types appear in Table 2. References for the photometric values in Cols. 7 and 8 are (h) Haug (1970), (hi) Hiltner (1956), (w) Wramdemark (1976) and (t) *Tycho* photometry (Høg et al. 2000). V values marked with a "*" indicate formal errors larger than 0.05 mag in *Tycho* photometry.

LS Number	BD/HD number	l	Position 1	Position 2	Spectral Type	V	$(B-V)$	Ref.	DM
III +46°19	–	85°.3	18/09 (1800)	19/09 (1800)	B1V+	11.38	0.61	w	12.0
III +45°54	–	87°.9	21/09 (2475)	20/09 (2515)	B3Ib	11.49	0.39	w	15.7
III +46°50	–	88°.8	21/09 (1800)	20/09 (1800)	O9.5III	10.69	0.72	w	13.1
III +53°32	–	99°.8	18/09 (1200)	19/09 (1200)	B2Ib	10.69	0.40	w	14.8
III +52°31	–	100°.0	18/09 (1200)	19/09 (1200)	(−)	10.79	0.23	w	(−)
III +55°19	–	100°.5	18/09 (1200)	19/09 (1200)	B0III*+?	10.64	0.63	w	13.3
III +59°19	–	103°.4	21/09 (2400)	20/09 (2400)	B1.5III*	11.02	0.56	w	12.6
III +55°88	–	103°.8	31/07 (1000)	01/08 (1500)	B0.2IV	11.15*	0.28	t	14.0
III +57°112	–	108°.5	18/09 (1500)	–	(−)	10.55	0.81	w	(−)
III +58°70	–	108°.8	–	19/09 (1800)	(−)	11.32	0.45	w	(−)
I +60°33	–	115°.3	18/09 (1800)	19/09 (1800)	B0III+	10.97	0.61	h	13.7
I +60°37	+59°2779	115°.4	18/09 (1500)	19/09 (1500)	B0.2V	10.48	0.78	h	11.3
I +62°23	+62°2296A	115°.8	18/01 (600)	19/01 (720)	B2.5Ia	8.64	1.07	h	12.3
I +60°46	+60°2631	115°.8	18/01 (600)	19/01 (750)	B0.5III	9.65	0.51	h	12.4
I +60°51	+60°2635	115°.9	31/07 (900)	01/08 (900)	ON7III(f)	10.13	0.46	h	13.5
I +63°22	+63°2084	117°.2	18/01 (600)	19/01 (720)	B2III	9.20	0.25	t	11.5
I +60°77	225146	117°.2	18/01 (600)	19/01 (600)	O9.7Ib	8.59	0.38	h	12.7
I +62°59	+62°2353	117°.4	18/01 (720)	19/01 (750)	B0.5III	9.88	0.24	h	13.5
I +63°57	+63°18	119°.0	18/09 (1000)	19/09 (1000)	B0.2IIIe	10.24	0.53	w	≳13.0
I +61°153	–	119°.9	18/09 (1800)	19/09 (1800)	B2III	11.13	0.14	h	13.8
I +62°107	+61°90a	120°.3	18/09 (1000)	19/09 (1200)	B0.5V+	10.20	0.18	h	12.7
I +62°113	+62°89	120°.5	18/09 (1000)	19/09 (1200)	B1.5Ve	10.15	0.49	h	≳10.8
I +60°247	+59°524	135°.9	18/09 (1800)	19/09 (1800)	B0.7II-III	10.95	0.63	t	13.1
I +57°138	–	146°.3	20/01 (1000)	19/01 (1000)	O7V	10.09	0.28	h	13.2
I +57°139	+56°864	146°.3	20/01 (900)	19/01 (900)	O6V+	9.67	0.28	h	>13.0
I +56°97	BD +56°866	146°.4	20/01 (1200)	21/01 (1200)	O9V	10.33	0.34	h	12.8
I +55°55	+55°837	147°.0	–	25/02 (1500)	B1Ib*	9.59	0.69	h	12.9
I +56°99	237211	147°.1	18/01 (720)	19/01 (700)	O9.5Iab	9.00	0.49	h	13.0
V +56°56	25914	147°.4	20/01 (750)	22/05 (1000)	B5Ia	7.99	0.60	hi	12.9
V +55°11	237213	147°.6	20/01 (900)	22/05 (900)	B6Ia	8.72	0.77	hi	13.2
V +56°59	–	149°.7	20/01 (1800)	–	B1V*+	10.92	0.25	t	12.6
V +56°60	–	149°.8	20/01 (1800)	21/01 (1550)	B2.5III	11.51*	0.24	t	13.7
V +53°22	232947	151°.6	18/01 (720)	19/01 (750)	B0Ia	9.32	0.64	hi	13.3
V +40°47	BD +39°1328	169°.1	18/01 (750)	19/01 (1000)	O9Ibf	9.85	0.57	hi	13.6
V +33°36	HD 243827	174°.3	18/01 (900)	19/01 (1200)	B0.2III	10.61	0.45	hi	13.6
V +25°20	–	185°.5	18/01 (1800)	19/01 (1200)	B0.3V	10.40	0.21	t	13.0
V +22°5	248893	186°.8	20/01 (1000)	25/02 (1200)	B0III	9.75	0.25	t	13.4
V +22°38	–	188°.8	20/01 (2000)	25/02 (2400)	B0.2III*(+)	10.76	1.01	h	12.0
V +20°20	252535	190°.0	18/01 (600)	19/01 (1000)	B1.5V(+)	10.09	0.19	h	11.6

it is assumed to be the continuation of the Norma Arm and therefore a main spiral feature. However, its definition is much less clear in the second quadrant, where the Cygnus Arm must lie basically beyond the Perseus Arm and its tracers are sparse.

The presence of elements very clearly belonging to the Cygnus Arm in the first Galactic quadrant and again in the Anticentre region and third quadrant is naturally suggesting that the Cygnus Arm must also exist in the second quadrant. Evidence for H I structure beyond the Perseus Arm has been collected from radio observations (e.g., Kulkarni et al. 1982; see also references in Wakker & van Woerden 1991). Russeil (2003) finds several star-forming regions likely associated with the Cygnus Arm, but she is unable to decide whether these are actually organised into an arm structure. It has been suggested (e.g., Quillen 2002) that the morphology of the outer Milky Way could be essentially flocculent.

Kimeswenger & Weinberger (1989), collecting a large amount of data from the literature, carried out a statistical analysis of the distribution with distance of spiral tracers in the second quadrant. They concluded that the Cygnus Arm is well

Table 2. Distant OB stars observed from the 1.93-m OHP telescope. LS I +60°78 is also known as BD +60°2664 and LS II +28°12 is listed as HD 332907. References for the photometric values in Cols. 6 and 7 are (tu) Turner (1980), (h) Haug (1970), (w) Wramdemark (1976), (w2) Wramdemark (1981) and (t) *Tycho* photometry (Høg et al. 2000).

LS Number	l	Date	Exposure Time (s)	Spectral Type	V	$(B-V)$	Ref.	DM
II +28°12	64°.4	06/07	650	B0.7II	10.91	0.45	tu	14.2
III +47°39	91°.3	07/07	1200	B1II	11.76	0.90	w	13.5
III +47°41	91°.3	07/07	1200	B1III	12.44	0.71	w	13.9
III +52°17	98°.5	06/07	1200	B2IV	12.25	0.43	w	13.4
III +52°19	98°.6	06/07	1200	BN1IIIe	12.04	0.44	w	$\gtrsim$ 14.3
III +52°31	100°.0	07/07	750	B1.5Ve	10.79	0.23	w	$\gtrsim$ 12.2
III +52°32	100°.0	07/07	750	B2IV	10.43	0.06	w	12.7
III +55°20	100°.4	07/07	900	BN0IV	11.07	0.77	w	12.6
III +59°29	107°.3	06/07	750	B0.7III	11.17	0.66	w	13.2
III +57°111	108°.4	06/07	900	B0.2III	10.32	0.61	t	12.8
III +57°112	108°.5	06/07	900	B0.3III	10.55	0.81	w	12.5
III +58°70	108°.8	06/07	1200	B0V	11.32	0.45	w	13.3
III +58°71	108°.9	06/07	1200	B0.3V	12.12	0.43	w2	14.0
I +59°10	113°.9	07/07	900	B0.2III	10.81	0.80	h	12.7
I +62°43	116°.3	07/07	1800	B2IV	12.34	0.37	h	13.6
I +62°44	116°.3	07/07	1800	B2.5IV	12.56	0.47	h	13.6
I +60°78A	117°.2	06/07	750	B1V	10.62	0.37	h	12.0
I +60°78B	117°.2	06/07	750	B1.5V	10.65	0.33	h	11.7

defined in the sense that, when considering spiral tracer counts with distance, a statistically significant gap exists between the Perseus Arm and a second maximum at ~5 kpc. Though the results of Kimeswenger & Weinberger (1989) are highly significant, their procedure is affected by a number of factors that limit their validity: they use data from a large variety of inhomogeneous sources, estimate most of their distances from photometric data only and do not have sufficient distant tracers to attempt the study of their spatial distribution (for example, at $l = 90°$, the Cygnus Arm is expected to be at 6–7 kpc, while at $l = 150°$, it should be at 4–5 kpc; cf. Vallée 2002).

In an attempt to obtain a more uniform data sample, we have started a programme to study the distance to different spiral tracers. In this first paper, spectroscopic parallaxes are derived for a sample of OB stars spanning the whole of the Second Galactic Quadrant, whose photometric indices are reported in the literature to indicate large distances. More detailed spectroscopic and photometric studies of individual young open clusters and OB associations will be presented in successive papers.

2. Observations

Most observations have been carried out with the *Aurélie* spectrograph on the 1.52-m telescope at the Observatoire de Haute Provence (OHP) during three dedicated runs on 18th–24th September 2001, 18th–22nd January 2002 and 25th–28th February 2002. In addition, one single object (LS I +60°51) was observed during a different run on July 31st/August 1st 2001. The spectrograph has been equipped with grating #3 (600 ln mm^{-1}) and the Horizon 2000 2048 × 1024 EEV CCD camera (see Gillet et al. 1994 for a description of the instrument). In the classification region, this configuration gives a dispersion of 0.22 Å/pixel (resolving power of approximately 7000), covering a wavelength range of ≈440 Å. It is therefore necessary to observe two wavelength regions in order to span the classical classification region.

For this programme, the two regions selected were centred at λ = 4175 Å and λ = 4680 Å. In principle, all objects were intended to be observed in both regions, resulting in coverage in the $\lambda\lambda$3950–4900 Å range, with a small gap (~60 Å) around λ4425 Å. No strong photospheric lines are found in the gap, but the strong diffuse interstellar line (DIB) at λ4428 Å, which is a good indicator of the reddening, is lost. However, due to the weather, only the equivalent of 6 whole nights could be used for observing and a small number of objects were only observed in one position. Fortunately, for most spectral types in the range considered any of the two regions allows an accurate spectral classification.

The complete log of observations at the 1.52-m OHP is given in Table 1. In addition to the stars listed, Position 2 observations were obtained on 20th Sep 2001 for LS I +62°99 and LS I +62°119. However, since the Signal-to-Noise Ratio (SNR) of these spectra is very low (due to thick veiling) and both objects appear to be Be stars (as Hβ seems in emission), no spectral types have been derived.

Several stars were observed on the nights of 6th and 7th July 2002 using the 1.93-m telescope at the OHP, France. The telescope was equipped with the long-slit spectrograph *Carelec* and the EEV CCD. The 1200 ln mm^{-1} grating was used, giving a nominal dispersion of ≈0.45 Å/pixel over the range 4000–4900 Å. The spectral resolution is ≈1.5 Å. The observations from the 1.93-m OHP are listed in Table 2.

Finally spectra of a few objects in the Galactic Anticentre were obtained on the nights of December 5–7th 2001 using the Andalucia Faint Object Spectrograph and Camera (ALFOSC) on the 2.6-m Nordic Optical Telescope (NOT), in La Palma, Spain. The telescope was equipped with a thinned

Table 3. Distant OB stars observed from the NOT. References are (h) Haug (1970), (m) McCuskey (1967) and (t) *Tycho* photometry (Høg et al. 2000). Note that M +22°178 is taken from McCuskey (1967) and does not have an LS number. Photometry from McCuskey (1967) is likely to be rather inaccurate. Spectral types for these objects are rather less accurate than for stars in Tables 1 and 2.

LS Number	l	Date	Exposure Time (s)	Spectral Type	V	$(B-V)$	Reference	DM
V +22°6	186.°3	07/12	600	B1V	10.96	0.34	t	12.4
V +23°8	186.°4	05/12	700	O8Iaf	10.83	1.25	m	12.5
M +22°178	186.°6	05/12	750	B2.5III*	12.33	1.04	m	12.1
V +22°50	189.°7	07/12	600	B2IVe	11.47	0.22	h	13.2
V +19°2	191.°5	07/12	900	B1.5III*	12.06	0.58	h	13.5

2048 × 2048 pixel Loral/Lesser CCD. Spectra were taken with grism #7 and the slit width was set to 1.′0, resulting in a spectral resolution of ≈6.6 Å. The log of these observations is given in Table 3.

All the spectroscopic data have been reduced with the *Starlink* packages CCDPACK (Draper et al. 2000) and FIGARO (Shortridge et al. 1997) and analysed using FIGARO and DIPSO (Howarth et al. 1997).

3. Target selection and methodology

For this programme, we have selected relatively bright stars given in the literature as candidates to distant OB stars because of their colours. These objects concentrate in a few interesting regions of the second Galactic quadrant. The location of Cygnus Arm stars in the first quadrant is to be a very difficult task, because of the large distance and strong absorption due to the Orion Spur. The stars observed have been mainly selected from Haug (1970) and Wramdemark (1976), but other sources have been used (mostly those given in Kimeswenger & Weinberger 1989). The exposure times needed with the configuration used at the OHP 1.52-m telescope make advisable not to observe stars with apparent magnitudes $B \gtrsim 12.5$, though a few slightly fainter objects have been observed with the larger telescopes.

In any case, the limit imposed by the instrumentation is approximately coincident with the magnitude limit of the Luminous Star (LS) catalogues (though they are not complete to this depth), beyond which there are very few available sources for candidates – fainter OB stars have not in general been identified as such and photometric data are not available. Therefore the sample observed cannot at all intend to represent in any significant way the population of massive stars in the Cygnus Arm, but rather consists only of a few glimpses through windows of low absorption in the Perseus Arm.

In order to derive spectroscopic parallaxes, accurate photometry (at least in B and V) is necessary. From the derived spectral type and measured $(B-V)$, one can then calculate $E(B-V)$, making use of tabulated calibrations of the intrinsic colour $(B-V)_0$ corresponding to each spectral type. Assuming then a standard value for the ratio of total to selective absorption R, a value for the visual extinction A_V is derived. The resulting magnitude corrected for reddening can then be used to derive the distance modulus (DM), making use of a calibration of absolute magnitude for a given spectral type.

There are many sources of uncertainty in this procedure. In principle, if the observational data are accurate, the two main sources of uncertainty are the value of R and the intrinsic dispersion in the absolute magnitude calibration. For a given spectral type, a dispersion of several tenths of a magnitude in the absolute magnitude calibration is normal among O-type and early B-type stars (cf. Walborn 2002, and references therein). The value of R can be locally very different from the Galactic average $R = 3.1$ (Fitzpatrick 1999). Both effects lead to a rather large dispersion in the derived DM, but assuming that deviations from standard values are random in nature, they can be compensated by observing a high number of stars.

Systematic effects are more difficult to correct. The absolute magnitude calibration for O-type stars is still debated. From an analysis using plane-parallel, non-LTE, pure H and He hydrostatic models, Vacca et al. (1996) derived a higher temperature scale and brighter magnitudes than previous calibrations (e.g., Humphreys & McElroy 1984). More recent models, including line blanketing, sphericity and mass loss (e.g., Martins et al. 2002; Herrero et al. 2000) support lower effective temperatures and similar magnitudes to the calibration of Vacca et al. (1996). On the other hand, Bianchi & García (2002), from an analysis of *FUSE* spectra, find even lower effective temperatures and lower magnitudes.

As these difficulties have still to be solved, in this work, we will simply have to use a consistent magnitude scale. We will use the calibration of Humphreys & McElroy (1984) for spectral types B2 and later and the calibration of Vacca et al. (1996) for spectral types O9 and earlier. As there is an important discrepancy between these two calibrations around spectral type B0, where the absolute magnitude changes rather steeply with spectral type, we have opted for an interpolated calibration, which is given in Table 4. This calibration is similar, though not identical, to that used by Russeil (2003). We assume slightly brighter magnitudes for stars of spectral types O9.5-B0.5, after Vacca et al. (1996).

The calibration for intrinsic colours used is that of Wegner (1994). We have interpolated over intermediate spectral types not tabulated in this work, and assumed that luminosity class IV stars have the same intrinsic colours as main sequence stars.

In order to prevent systematic observational effects, a homogeneous dataset and analysis is fundamental for accurate distances. In this work, the spectroscopic dataset is homogeneous and the spectral classification has been done in a consistent way, reducing the possibility of artificial dispersion. A homogeneous photometric dataset, however, is not available in

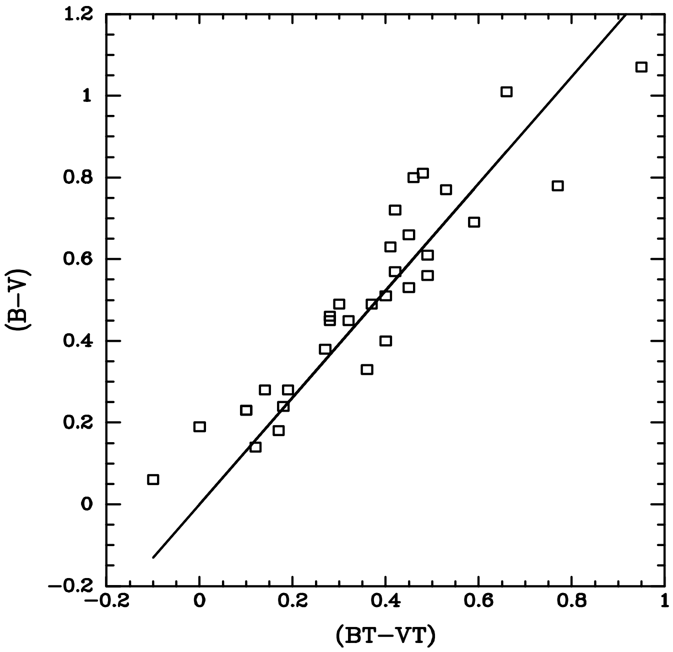

Fig. 1. Linear regression between photoelectric $(B-V)$ and *Tycho* $(B_T - V_T)$ for 30 stars in our sample for which both kinds of data exist. The linear fit provides a relationship $(B-V) = 1.31\ (B_T - V_T)$, with a correlation coefficient $R = 0.89$. This is very different from the standard relation for *Tycho* photometry, derived for unreddened stars.

the literature. This turns out to be the main source of systematic uncertainty in our results.

For a large fraction of our sample, photometry is available from the *Tycho* catalogue (Høg et al. 2000). It was therefore our initial intention to use this dataset as primary source for photometry. However, comparison of all existing photometric data for several objects showed very good agreement between different photoelectric measurements and large and *systematic* discrepancies between photoelectric and *Tycho* photometry.

It was observed that the $(B-V)$ colour was systematically larger in photoelectric photometry than when the standard transformation

$$(B-V) = 0.85(B_T - V_T) \quad (1)$$

from *Tycho* photometry (Høg et al. 2000) is applied. This effect is illustrated in Fig. 1. When a linear fit is applied to the 30 objects in our sample for which both *Tycho* and photoelectric photometry exists, a transformation

$$(B-V) = 1.31(B_T - V_T) \quad (2)$$

is derived, clearly very different from Eq. (1).

The existence of this difference is not surprising as Eq. (1) has been derived from a sample that mostly consists of nearby unreddened stars, while our sample wholly consists of reddened intrinsically blue stars. As a matter of fact, it appears from our small sample that the difference between photoelectric $(B-V)$ and the values derived from Eq. (1) increases with increasing $E(B-V)$ (calculated assuming the photoelectric values). This point should be investigated with a larger sample of stars for which reliable spectral types exist.

Table 4. Absolute magnitude calibration used here. For stars earlier than B0, it is based on the calibration of Vacca et al. (1996). For B spectral types, the calibration of Humphreys & McElroy (1984) has been used. In the B0-B1 interval, where the calibrations are very discordant, an interpolation has been made. For the only star with luminosity class Iab in the sample, HD 237211 (O9.5Iab), $M_V = -6.3$ has been adopted.

	V	IV	III	II	Ib	Ia
O6	−5.1	–	−5.8	–	–	−6.4
O7	−4.9	–	−5.7	–	–	−6.5
O8	−4.7	–	−5.6	–	–	−6.5
O9	−4.4	–	−5.5	–	−6.3	−6.5
O9.5/7	−4.3	–	−5.4	–	−6.0	−6.6
B0	−4.2	−4.7	−5.3	−5.8	−6.0	−6.6
B0.2/3	−4.0	−4.6	−5.1	−5.6	−6.0	−6.7
B0.5	−3.8	−4.5	−5.0	−5.5	−6.0	−6.9
B0.7	−3.5	−4.2	−4.8	−5.3	−6.0	−7.0
B1	−3.2	−3.8	−4.3	−5.1	−6.0	−7.0
B1.5	−2.8	−3.3	−3.9	−5.0	−5.8	−7.2
B2	−2.5	−3.1	−3.7	−4.8	−5.8	−7.4
B2.5	−2.0	−3.1	−3.5	−4.8	−5.8	−7.4
B3	−1.6	−2.5	−3.0	−4.7	−5.8	−7.2

In view of this discrepancy, we have opted for taking Haug (1970) as our prime source of photometry. Objects not observed by Haug (1970) have been taken from Wramdemark (1976), as this author has transformed his measurements to be in the same system used by Haug (1970) and Hiltner (1956), cf. Särg & Wramdemark (1977). For a few stars, we have taken photoelectric photometry from other sources, listed in Tables 1 and 2. Only when we have been unable to find *any* photoelectric photometry in the literature, have we resorted to *Tycho* photometry. For two stars in Table 3, no photoelectric or modern photometry existed. We have had to resort to photographic photometry from McCuskey (1967). Comparison of values from McCuskey (1967) for other stars with more modern photoelectric photometry shows that these photographic values may be in error by several tenths of a magnitude.

4. Results

For all stars observed accurate spectral types have been derived. For the majority of targets, the signal-to-noise ratio is sufficiently high to allow, at this resolution, an accuracy better than the subtype. Classification has been carried out by direct comparison to MK standards observed at similar (or slightly lower) resolution and the digital atlas of Walborn & Fitzpatrick (1990). We followed the guidelines for classification from Walborn & Fitzpatrick (1990), complemented by the spectral atlas of Lennon et al. (1992) for the supergiants. For O-type stars, the procedure of Walborn & Fitzpatrick (1990) has been complemented by the quantitative relations of Mathys (1988), based on Conti's scheme. In all cases, both methods have given excellent agreement, demonstrating once again their consistency.

Once a spectral type was obtained, we calculated a distance modulus following the procedure described in the previous section. The distribution of stars with distance has been studied by dividing the sample into several individual regions. A histogram plot showing the distribution in three of those areas is shown in Fig. 3.

4.1. Vulpecula

In the Vulpecula and Cygnus region, the study of the Cygnus Arm is complicated by the fact that distances are very large and the Orion Spur runs almost parallel to the line of sight, resulting in heavy obscuration and poorly defined distances. In his study of Vul OB2, Turner (1980) determined a dereddened distance modulus $DM = 13.2$, placing this association at 4.4 kpc, in good agreement with the expected position of the Perseus Arm (Vallée 2002). We searched for candidates for Cygnus Arm stars in the works of Turner (1980) and Forbes (1985), but few appeared convincing.

The only star we have observed is LS II +28°12. The derived spectral type B0.7II implies $DM = 14.2$ using the photoelectric photometry from Turner (1980). This value is rather larger than the distance to the Perseus Arm, but still shorter than the $DM \approx 14.8$ compatible with the ≈9 kpc distance to the Cygnus Arm in this direction (Vallée 2002). The case therefore remains inconclusive.

4.2. The Cepheus region

The Cep OB1 association extends, according to Humphreys (1978), from $l = 98°$ to $l = 108°$. Garmany & Stencel (1992) list numerous members, but warn that it could well really consist of two independent associations, centred on the Eastern and Western sides of this range (cf. Moffat 1971). The reality of this association has also been disputed by other authors (e.g., Mel'nik & Efremov 1995). Assuming it is a single association, Garmany & Stencel (1992) derive a $DM = 12.2$.

We have observed 19 stars over the longitude range $85° < l < 110°$, 14 of which lie within the traditional limits of Cep OB1. The spectrum of LS III +55°20 seems to be moderately N enhanced and rather C deficient. LS III +52°19, apart from being a Be star, also seems to be C deficient. Another Be star in this range is LS III +52°31. The distances to Be stars should be taken as lower limits, since part of the $E(B-V)$ excess will be due to circumstellar emission and not interstellar absorption and also because Be stars tend to be slightly brighter than normal stars of similar spectral types. These two factors are unlikely to result in a difference much larger than 0.3 mag.

Seven stars turn out to have $DM \leq 12.8$. The distances to LS III +46°19 and LS III +52°31 must be considered lower limits, as they are respectively a double-lined spectroscopic binary and a Be star. The distances to the other five objects cluster quite tightly, with an average $\overline{DM} = 12.64 \pm 0.10$ (errors in averages indicate 1-σ deviations). The true distance moduli to LS III +46°19 and LS III +52°31 are likely to be compatible with this value. The corresponding distance $d = 3.4$ kpc is moderately larger than the distance derived to Cep OB1 by Garmany & Stencel (1992), but clearly consistent with the distance to NGC 7380, believed to be its nuclear cluster, derived by other authors. For example, photometric determinations give $DM = 12.5$ (Baade 1983; Chavarría-K. et al. 1994), while Massey et al. (1995) find $DM = 12.9 \pm 0.1$ from spectroscopic parallaxes of 10 stars. Therefore this seven stars in our sample appear to be members of Cep OB1 and hence be located on the Perseus.

Six stars have $13.1 \leq DM \leq 13.5$. The average is $\overline{DM} = 13.3 \pm 0.1$. There appears to be a clear gap between this group and the Perseus Arm group. Moreover, this is the most obvious concentration of stars in this region (see Fig. 3), though the corresponding distance $d = 4.6$ kpc does not fit well with the position of any Galactic arm in current models, unless the Perseus Arm is considered to be very broad.

The remaining six stars have $DM \geq 13.9$. Again there is a significant gap with respect to the previous group (see Fig. 3). Three stars cluster very tightly around $DM = 14.0$, but adding LS III +52°19 and LS III +53°32, we obtain an average $\overline{DM} = 14.2 \pm 0.3$. The corresponding distance $d = 7$ kpc is consistent with the expected position of the Cygnus Arm.

The $DM = 15.7$ to LS III +45°54 is remarkably large, implying $d = 13.8$ kpc. The photometry is not in error, as Drilling (1975), gives $V = 11.52$, $(B-V) = 0.38$, in very good accordance with Wramdemark's values. Reducing the luminosity class to B3II would lower the DM to 14.6, more in line with other tracers of the Cygnus Arm, but the spectrum looks that of a supergiant (see Fig. 2).

4.3. Cassiopeia

Based on photometry of stars in the LS catalogue, Haug (1970) suggested that over a rather large region of the Galactic plane, centred on the association Cas OB5, there was a significant population of OB stars at a rather larger distance than the objects considered to be members. This suggestion was supported by further photometric (Wramdemark 1976) and spectroscopic (Martin 1972) studies.

Cas OB5 is a well populated OB association extending from $l \approx 115°$ to 118° (Humphreys 1978). There is no obvious core cluster associated, rendering a distance determination unsure. According to Garmany & Stencel (1992), members define a fairly clear main sequence at $DM = 11.5$. Almost coincident with it is Cas OB4. It extends from $l \approx 119°$ to 122° (Humphreys 1978) and, though sparse, it fits well a $DM = 12.2$ (Garmany & Stencel 1992). Members are of rather late spectral type (earliest spectral type is O9V) and there is no nuclear cluster.

Over the $112° \leq l \leq 121°$ range, we have observed 17 stars. Among the stars observed, LS I +60°33 and LS I +62°107 present evidence for a second spectrum of similar spectral type and therefore could have larger DM. LS I +62°23 = BD +62°2296A has been found to be part of an apparent triple system, including a B0III and a WN4 companion. These companions are unlikely to contribute much to the total luminosity. The system will be discussed in a separate work. Two of the stars observed in this region, namely LS I +63°57 and LS I +62°113, are Be stars. Their distances are therefore likely to be slightly larger than calculated.

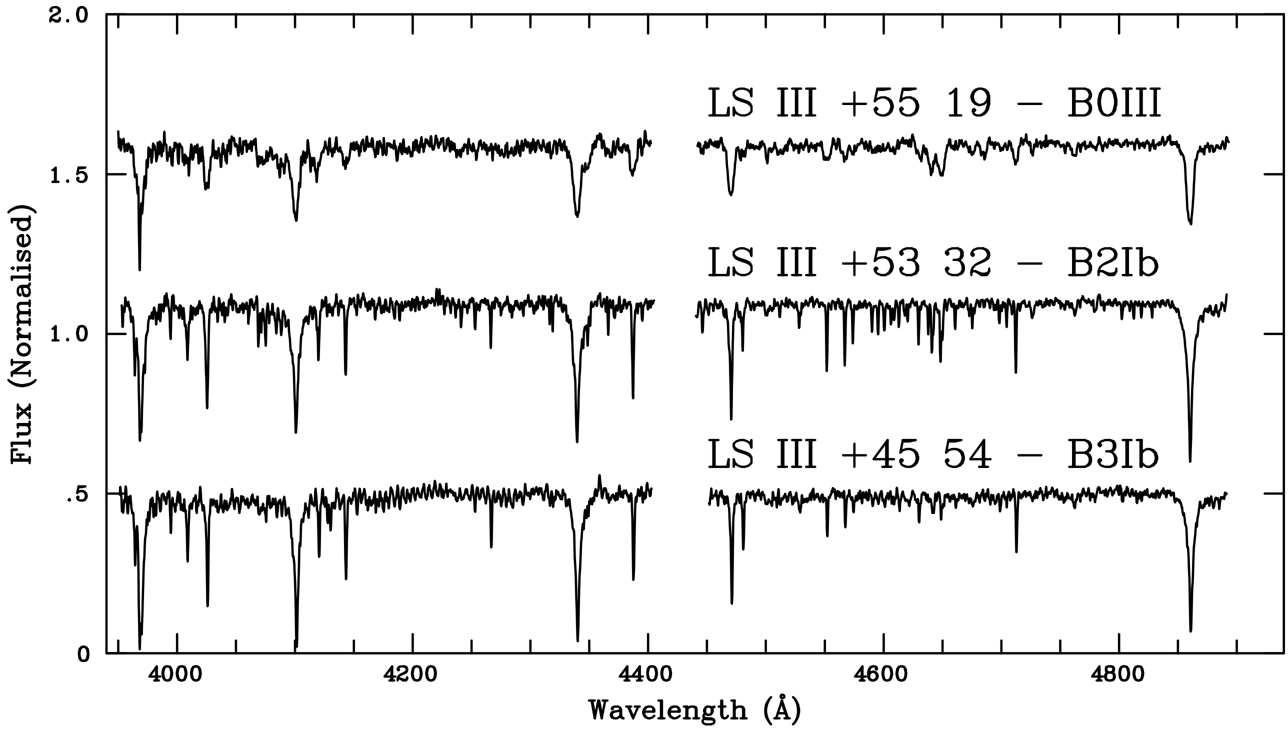

Fig. 2. Likely tracers of the Cygnus Arm in the l = 85°−105° range observed with the OHP 1.52-m telescope. The small gap around λ = 4420 Å indicates the division between the two poses. LS III +53°32 and LS III +45°54 have spectroscopic distances well in excess of d = 7 kpc.

We find a spread of objects over the DM = 11−13 range. A few of them have distance moduli compatible with the accepted distance to Cas OB5 (LS I +60°37, LS I +63°22 and LS I +62°113), but, if there is any concentration of stars, it lies at $DM \approx 12.6$. Again this distance does not correspond well to any arm, unless we assume that the Perseus Arm is very broad. Moreover, most of the objects in the DM = 12−13 range (marginally compatible with the distance to Cas OB4) are located within the longitude range assigned to Cas OB5. Therefore we do not find a clear definition between Cas OB5 and Cas OB4.

There is, however, a clear gap with respect to the objects with $DM \geq 13$ (see Fig. 3). Leaving aside the Be star LS I +63°57, we find six objects with distance moduli clustering tightly around $\overline{DM} = 13.6 \pm 0.1$, corresponding to d = 5.3 kpc. This group almost certainly corresponds to the tracers of the Cygnus Arm over this segment. Of particular interest is LS I +60°51 (BD +60°2635). It is an O-type star of moderate luminosity with strong N III emission (see Fig. 5), for which we derive a spectral type ON7III(f).

Walborn (2002) has shown that most of the O-type stars traditionally associated to Cas OB5 have *DM*s indicating rather larger distances. The revised *DM*s calculated by Walborn fall in the 12−13 range, in good agreement with our sample. Obviously this region merits further study and a dedicated work is forthcoming.

4.4. Cam OB3

Beyond $l \approx 140°$, the Perseus Arm is not very well defined. This is surprising considering that the spectacular Per OB1 and Cas OB6 associations extend until this Galactic longitude, but it seems to be due to a real lack of spiral tracers and not to local extinction. Orion Spur associations are, however, present in the l = 140°−180° range, notably Cam OB1 and Aur OB1.

Cam OB3 is a rather diffuse OB association, containing no known open clusters. Its existence has sometimes be considered doubtful and it is not included in the work of Garmany & Stencel (1992). However, Haug (1970), based on *UBV* photometry of a large number of LS stars, had considered its existence certain. Using data in the literature for 6 likely members, Humphreys (1978) centred it at (l = 147°, b = +3.0) and derived DM = 12.6. This is one magnitude larger than the *DM*'s to Per OB1 and Cas OB6, the tracers of the Perseus Arm closest in the sky. Moreover, considering that the Perseus Arm is running towards its minimum distance to the Sun in this region, Cam OB3 is clearly too far away to be on the Perseus Arm.

We have obtained spectra for ten stars in the area of Cam OB3, among which we note the following peculiarities:

– HD 25914 is a known variable, GQ Cam, and radial velocity measurements in the literature are rather inconsistent, suggesting binarity. Its DM is likely then to be underestimated.
– The spectral type for HD 237213 is B6Ia, rather different from the B3Ia given by Morgan et al. (1955). Photometric measurements by Fernie (1983) and Hiltner (1956) are rather discordant as well.
– BD +56°864 has been classified as O6Vnn. However, at the resolution of our spectra, it is clear that the very broad lines are due to the presence of two components in the lines. The two components are much more clearly

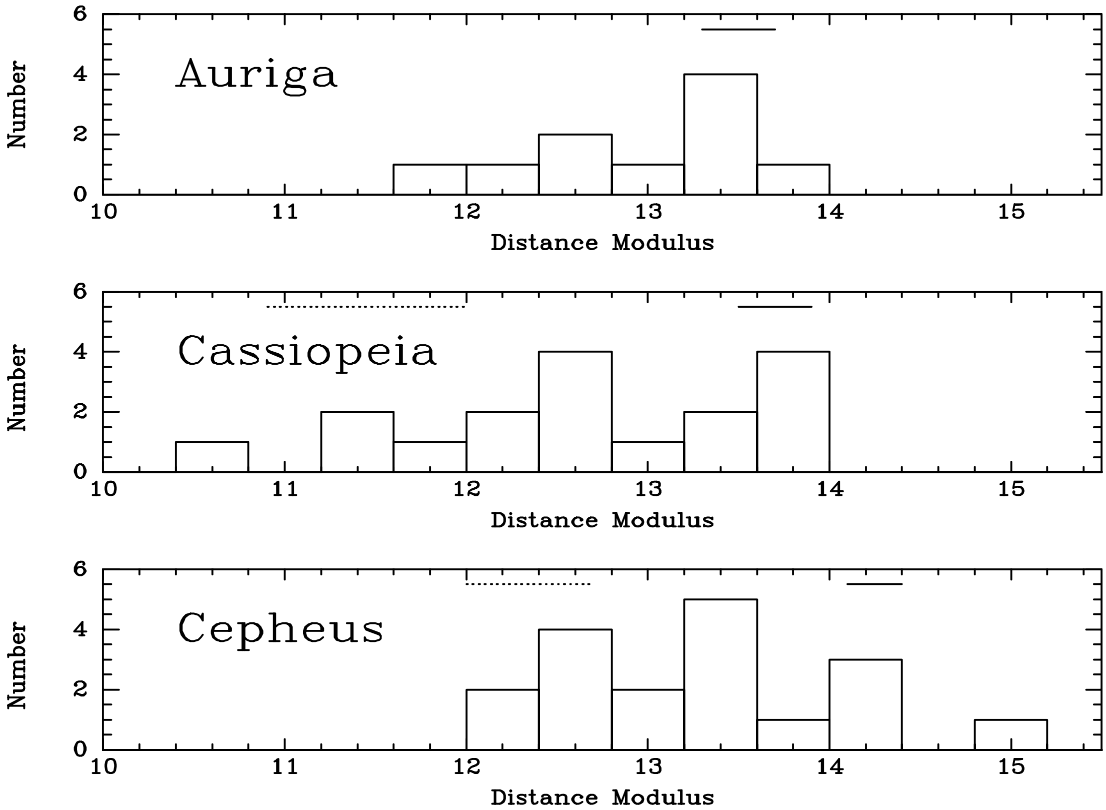

Fig. 3. Histogram showing the spread of stars with distance modulus in three of the regions considered in the text. Stars are arbitrarily grouped in 0.4-mag bins. Dotted lines on top of the graphs show the traditionally-accepted extent of the Perseus Arm in the Cepheus and Cassiopeia regions, while continuous lines show the estimated position of the Cygnus Arm, from the model of Vallée (2002). In all cases, the arms are assumed to have a width of 1 kpc. In all three regions there are obvious concentrations of stars at distances compatible with the Cygnus Arm. Note that the distance to LS III +45°54 is too large to fit in the figure. Also note that all stars in our sample were selected because their photometric indices suggested that they were very distant objects. As the original intention was not to include any Perseus Arm objects, the distribution shown here is not representative *at all* of the total distribution of stars.

separated in the Position 2 spectrum than in Position 1. BD +56°864 is therefore a double-lined spectroscopic binary. The two components have similar spectral types, approximately O6V((f)), and therefore the DM is likely to be underestimated by several tenths of a magnitude.

The eight objects with photoelectric photometry give an average $\overline{DM} = 13.0 \pm 0.2$. The low dispersion, specially when considering that most stars observed are supergiants, represents strong confirmation of the existence of Cam OB3. LS V +56°60, with *Tycho* photometry, gives a larger distance modulus. If we transform the *Tycho* magnitudes using Eq. (2) instead of Eq. 1, we find $DM = 12.2$ and 13.3 for LS V +56°59 and LS V +56°60 respectively, compatible with all the other stars in the area, if we take into account that LS V +56°59 is a double-lined spectroscopic binary.

The distance modulus to Cam OB3 is almost two magnitudes larger than would be expected if it was in the Perseus Arm. We therefore conclude that Cam OB3 is a tracer of the Cygnus Arm. A more comprehensive study of this association will be presented in future work.

4.5. Auriga/Gemini

Galactic structure in the direction of the Anticentre is rather complex. Traditionally, two OB associations have been considered to exist in the range $l = 170°–180°$. In her compilation of Galactic OB associations, Humphreys (1978) lists 12 likely members of Aur OB1, with an average distance modulus $DM = 10.6$, extending over a vast region spanning from $l_{\rm II} = 168°$ to 178° and from $b = -7.4°$ to $b = +4.2$. Considering its distance, Aur OB1 should be located in the Orion Spur, but some authors (e.g., Mel'nik & Efremov 1995) doubt its existence.

On the other hand, Aur OB2 is given as a rather more distant and compact association, extending between $l_{\rm II} = 172°$ and 174° from $b = -1.8$ to $b = +2.0$. The very young open cluster NGC 1893, containing several O-type stars, has been traditionally considered its core. Humphreys (1978) lists only 8 members of Aur OB2 and adopts $DM = 12.5$. This value, however, is just an average between the distance to NGC 1893 (taken as $DM = 12.8$) and the rather lower values for other presumed members.

All modern work based on accurate photometry has resulted in much larger distances to NGC 1893. Fitzsimmons (1993) found $DM = 13.4$ from Strömgren photometry, while Marco et al. (2001) derived $DM = 13.9$. Such large values are incompatible with the distances to other putative members and suggest that Aur OB2 must be separated into at least two groupings.

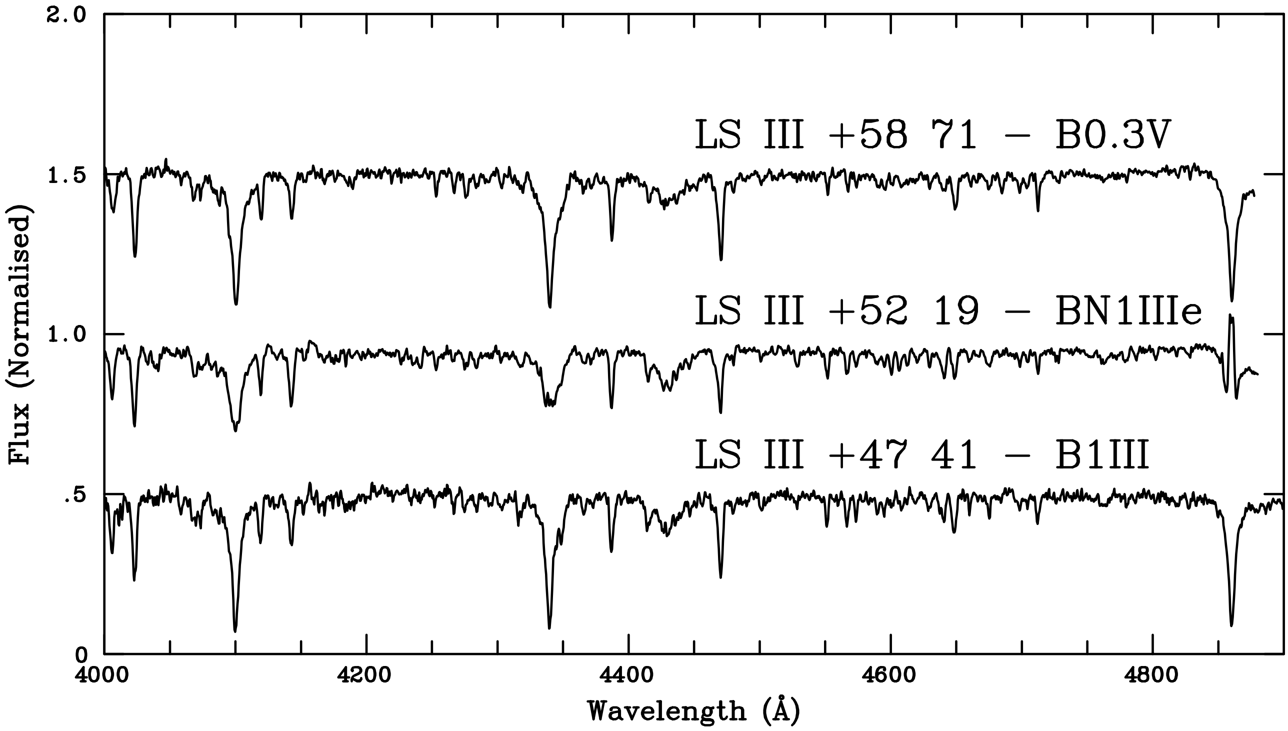

Fig. 4. Likely tracers of the Cygnus Arm in the region of Cep OB1 observed with the OHP 1.93-m telescope.

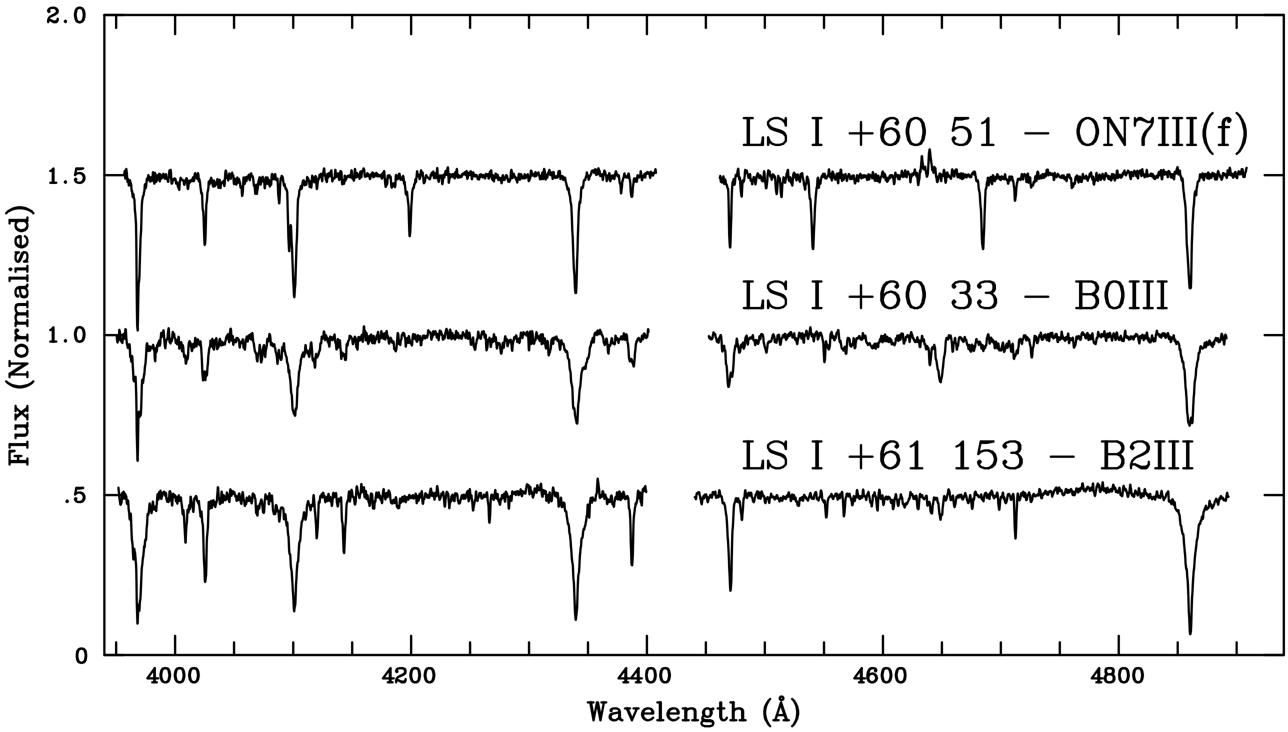

Fig. 5. Likely tracers of the Cygnus Arm in the region of Cas OB5 observed with the OHP 1.52-m telescope. LS I +60°51 has one of the earliest spectral types observed in this survey. The small gap around λ = 4420 Å indicates the division between the two poses.

The two stars in our sample with Galactic longitude close to l = 170° (LS V +40° 47 and LS V +33° 36) have DM = 13.6 and 13.7 respectively, in good agreement with the distance to NGC 1893. In the interval l = 186°−192°, most stars in our sample have distances compatible with a prolongation of the Perseus Arm, though the photometry is not very reliable for some of our objects. Of particular interest is LS V +23° 8, which, if we trust the photographic photometry of McCuskey (1967), is an obscured O8 supergiant lying in the Perseus Arm. This possible prolongation of the Perseus Arm would be

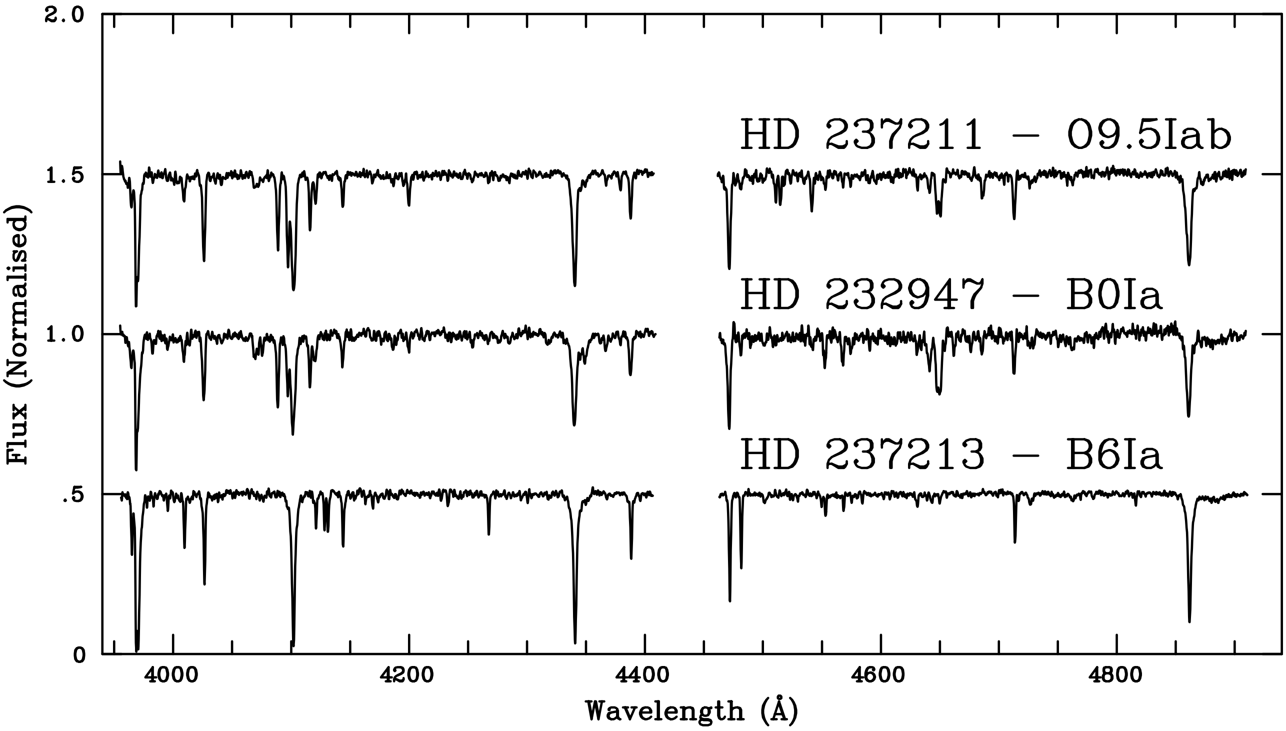

Fig. 6. Blue spectra of supergiant stars in Cam OB3. The small gap around $\lambda = 4420$ Å indicates the division between the two poses. All these objects have $DM \geq 13.0$.

marked by objects in Aur OB2 not associated with NGC 1893, likely connected with the young open clusters Stock 8 (Mayer & Macak 1971) and NGC 1931 (Pandey & Mahra 1986), both at $DM \approx 12$. Such distant objects cannot be associated with the Orion Spur in this direction ($l = 174°$).

Only three out of nine objects in this range have distances placing them close to the Cygnus Arm.

5. Discussion

5.1. Validity of the method

As outlined in Sect. 3, the method of spectroscopic parallaxes cannot be considered very accurate in the determination of the distance to a single star, but the different sources of non-systematic uncertainties tend to cancel out when a large sample is considered. Unfortunately, in this work we are covering a large span of the Galactic plane and therefore the objects in any of the individual areas surveyed represent only a moderately-sized sample.

In order to assess the dispersion that we could expect in our determinations of *DM*, we observed with the OHP 1.93-m several pairs of stars of similar magnitude lying very close in the sky (see Table 2), in the hope that they might also be physically related. In all cases, we found that the spectral types of the two stars were very similar, suggesting that a physical association did indeed exist. Of the seven cases considered, we find five pairs of stars for which the difference in *DM* is sufficiently small to be explained solely by a dispersion of ∼0.3 mag in the intrinsic magnitude calibration. The two exceptions, LS III +52°17 and 19 and LS III +58°70 and 71, show differences that would need a rather larger dispersion, but can also be explained by assuming that one of the two stars is actually an unresolved binary.

As a matter of fact, the presence of unrecognised binaries in the sample is likely to be a major contributor to the dispersion in *DM* observed within one single area. In order to test the statistical significance of the different groupings of stars, one would need to observe a large sample of objects in a small region. Such a study will be conducted in a forthcoming paper.

5.2. Representativity of the sample

The objective of this work was simply confirming the existence of OB stars at distances compatible with the position of the Cygnus Arm. Candidates were selected from the catalogues of luminous stars because of their colours. Most of them are intrinsically very bright objects with moderate reddening. As can be seen in Tables 1 and 2, most of the objects which turn out to have $DM \geq 13$ have luminosity classes I-III. This is a bias inherent to the selection procedure, as we are picking up very distant objects in a magnitude-limited sample.

Obviously, this sample is not representative of the population of OB stars in the Cygnus Arm, but made up of the few bright objects that happen to be seen through windows of low absorption in the Orion Spur and the Perseus Arm. A better idea of the sort of apparent magnitudes and reddenings characterising the OB population of the Cygnus Arm can be obtained with the following.

In their comprehensive spectroscopic study of some OB associations of the Northern Milky Way, Massey et al. (1995) obtained spectra of all stars with blue colours in their fields,

Table 5. Background early-type stars observed by Massey et al. (1995) in Perseus Arm fields. Spectral types and photometric measurements are from Massey et al. (1995), while the corresponding *DM* have been calculated with the calibration used here.

Field	Coordinates (J2000)	l	Spectral Type	V	$(B-V)$	DM
NGC 7235	22 13 30.34 +57 17 41.4	102°.8	B1.5V	14.67	0.98	13.8
NGC 7380	22 47 30.93 +58 09 07.8	107°.2	B3V	13.89	0.44	13.6
	22 47 52.01 +58 05 49.0	107°.2	B0.5V	15.53	1.12	15.1
Cep OB5	23 01 44.67 +57 05 56.6	108°.4	B2V	14.08	0.61	14.0
	23 02 42.22 +56 57 14.0	108°.5	B1.5V	14.48	0.75	14.3
IC 1805	02 31 48.47 +61 34 55.8	134°.6	B2V	13.93	0.76	13.4
	02 32 06.48 +61 29 54.2	134°.6	B1.5V	13.93	0.91	13.2
	02 33 09.06 +61 27 46.1	134°.8	B1V	12.93	0.65	13.4
NGC 2244	06 31 37.10 +04 45 53.7	206°.4	B0.5V	15.15	0.98	15.2
	06 32 22.49 +04 55 34.4	206°.4	B3V	15.39	0.67	14.4
	06 33 10.16 +04 59 50.2	206°.4	B3V	14.98	0.78	13.6

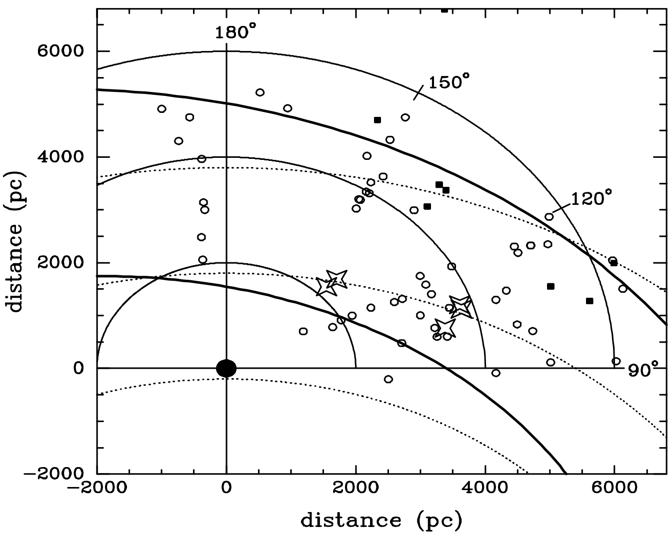

Fig. 7. Position of the stars under investigation in the Galaxy. The black dot at the coordinate origin represents the position of the Sun. Dotted arcs represent circles of Galactocentric distance 7, 9 and 11 kpc (assuming $R_{\odot}$ = 7.2 kpc). The three semicircles correspond to distances of 2, 4 and 6 kpc from the Sun, with Galactic longitude marked on the outermost semicircle. The thick traces are the logarithmic spiral arms corresponding to the Perseus Arm and Cygnus Arm in the model of Vallée (2002). Stars in our sample are shown as open circles, while stars from Table 5 are represented as filled squares. The large stars represent the locations of open clusters and associations considered to be good tracers of the Perseus Arm, NGC 7235, NGC 7380, Cep OB5, IC 1805 (distances from Massey et al. 1995) and h Per (distance from Marco & Bernabeu 2001).

independently of magnitude. They found a few OB stars far beyond the targeted fields in all the associations observed in the $l \approx 100°-210°$ range, except in the case of NGC 1893, which is itself on the Cygnus Arm. All these objects are listed in Table 5, where we have calculated distance moduli for them, based on the photometry of Massey et al. (1995).

Five stars from Table 5 fall in the Cepheus region. Among them, there is one with a very large $DM = 15.1$. The other four average to $\overline{DM} = 14.0 \pm 0.3$, in good agreement with our sample. Likewise, the three objects beyond the field of IC 1805 ($l \approx 136.6°$) agree quite well on $\overline{DM} = 13.3$, quite similar to the values found for our objects at $l \approx 120°$ and $l \approx 147°$.

The objects in Table 5 have on average spectral types indicating that they are rather less luminous than stars in our sample. They are also rather more obscured, which is consistent with their location behind star-forming regions of the Perseus Arm. As a consequence, they are several magnitudes fainter than objects in our sample. However, they are all within the reach of a moderate-size telescope with a modern spectrograph. Hence, it is to be expected that a sizable proportion of the OB population of the Cygnus Arm may be identified.

5.3. Is the Cygnus Arm well traced?

Moffat et al. (1979) estimate a $DM = 13.2 \pm 0.2$ for the young open cluster Waterloo 1, at $l = 151.4°$. For two other small groups of young stars associated with the H II regions Sh 2-217 and Sh 2-219 (at $l \approx 159.3°$), both of which contain embedded clusters (Deharveng et al. 2003), they estimate $DM = 13.1 \pm 0.3$ and $DM = 13.6 \pm 0.3$, while for NGC 1624 (at $l = 155.4°$), they estimate $DM = 13.9 \pm 0.2$. All these estimates are in good agreement with the *DM* we find for the nearby Cam OB3.

Three stars close to $l = 135°$ in Table 5 yield $\overline{DM} = 13.3$, intermediate between the values obtained for presumed tracers of the Cygnus Arm in the Cassiopeia region (Sect. 4.3) and for the Cam OB3 region. All these values support the idea of a coherent spiral structure with $d = 4-5$ kpc over the $l = 130°-150°$ range. This distance is slightly shorter than predicted by the models of Vallée (2002) or Russeil (2003) (in which the Cygnus Arm runs at ≈5 kpc), but certainly consistent with them, if we take into account the width of a spiral arm.

This structure is likely to be continued by the objects we find at $d = 5.3$ kpc around $l = 120°$ and the objects at $d = 6-7$ kpc at $l \approx 105°$. However, a larger sample of distant stars and some more secure distances (such as good photometric distances to open clusters) will be necessary in order to confirm the continuity of the Cygnus Arm over such a large span.

Over the $l = 160°-170°$ range there is a lack of possible Outer Arm tracers in the literature, but beyond $l = 170°$ there is a number of open clusters clearly delineating it (NGC 1893, Bochum 1 and 4 other clusters studied by Turbide & Moffat 1993). The existence of a structure at d = 5−6 kpc over the l = 175°−215° range seems rather secure.

6. Conclusions

We have carried out a spectroscopic survey of stars in the l = 85°−190° range reported in the literature to have photometric indices suggesting that they could be very distant OB stars. Over the whole range, we find a large number of objects whose spectroscopic parallaxes support a distance well above that expected for Perseus Arm stars and in relatively good agreement with the predictions for the position of the Outer or Cygnus Arm.

Over the l = 85°−115° range, tracers of the Cygnus Arm are not very numerous and sparsely located. Many of them are stars of high luminosity, suggesting that at these Galactic longitudes the main sequence B-star population of the Cygnus Arm is far too faint to appear in the LS catalogues even in the regions of lower extinction.

From l = 115°, tracers of the Cygnus Arm start to be more frequent. Several objects in the field of Cas OB5 and Cas OB4 give distance moduli clustered around DM = 13.6, suggesting that the Cygnus Arm is there at $d \approx 5.3$ kpc.

In the l = 140°−180° range, Perseus Arm tracers are rather inconspicuous, with the possible exception of some objects in Aur OB2. Over this range, most spiral tracers seem to belong to the Outer Arm, including the extended Cam OB3 association at $d \approx 4$ kpc and NGC 1893 and its surrounding area, which should be separated from other clusters in Aur OB2.

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