The star catalogues of Ptolemaios and Ulugh Beg

Machine-readable versions and comparison with the modern Hipparcos Catalogue[*]

Frank Verbunt[1,2] and Robert H. van Gent[3,4]

[1] Department of Astrophysics/IMAPP, Radboud University Nijmegen, PO Box 9010, 6500 GL Nijmegen, The Netherlands; e-mail: F.Verbunt@astro.ru.nl
[2] SRON Netherlands Institute for Space Research, Utrecht
[3] Until Jan.2010: URU-Explokart, Faculty of Geosciences, Utrecht University, PO Box 80 115, 3508 TC Utrecht, The Netherlands
[4] Institute for History and Foundations of Science, PO Box 80 010, 3508 TA Utrecht, The Netherlands; e-mail: :r.h.vangent@uu.nl

Abstract

In late antiquity and throughout the middle ages, the positions of stars on the celestial sphere were obtained from the star catalogue of Ptolemaios. A catalogue based on new measurements appeared in 1437, with positions by Ulugh Beg, and magnitudes from the 10th-century astronomer al-Sufi. We provide machine-readable versions of these two star catalogues, based on the editions by Toomer (1998) and Knobel (1917), and determine their accuracies by comparison with the modern Hipparcos Catalogue. The magnitudes in the catalogues correlate well with modern visual magnitudes; the indication 'faint' by Ptolemaios is found to correspond to his magnitudes 5 and 6. Gaussian fits to the error distributions in longitude / latitude give widths $\sigma \simeq 27'$ / $23'$ in the range $|\Delta\lambda, \Delta\beta| < 50'$ for Ptolemaios and $\sigma \simeq 22'$ /$18'$ in Ulugh Beg. Fits to the range $|\Delta\lambda, \Delta\beta| < 100'$ gives 10-15% larger widths, showing that the error distributions are broader than gaussians. The fraction of stars with positions wrong by more than $150'$ is about 2% for Ptolemaios and 0.1% in Ulugh Beg; the numbers of unidentified stars are 1 in Ptolemaios and 3 in Ulugh Beg. These numbers testify to the excellent quality of both star catalogues (as edited by Toomer and Knobel).

Key words. astrometry – history and philosophy of astronomy

1. Introduction

Ancient Greek astronomy culminated in the work of Ptolemaios, and in particular in his Mathematike Syntaxis, i.e. Mathematical Composition, of astronomy. By its pre-eminence this book, known in later ages by its Arabic name Almagest, eclipsed much of the earlier work, and thus its star catalogue with epoch 137 AD is the oldest extant major star catalogue that we have. Knowledge of the Almagest has reached the modern world in Arabic via the Arabic/Islamic culture, in particular through Spain, and in Greek via Byzantium. In both cases, the oldest manuscripts we have are copies of copies of copies..., and as a result one and the same star may have rather different positions in different manuscripts.

The Arabic manuscripts and the translation into Latin by Gerard of Cremona based on them have been studied by Kunitzsch (1974a), who also edited the star catalogue in these manuscripts (Kunitzsch 1986, 1990, 1991). A critical edition of the Greek text, based on the available Greek manuscripts, was produced by Heiberg (1898, 1903), and translated into German by Manitius (1913, reprinted with corrections by Neugebauer 1963). More recently, an English translation of the Almagest which takes into account both the Arabic and the Greek manuscripts has been made by Toomer (1984, 1998).

The medieval Arabic and Latin editions of star catalogues in general did not involve new observations. The star positions of Ptolemaios were merely updated by the addition of a constant to the ecliptic longitudes, to correct for precession. In the 10th century the Persian astronomer al-Sufi estimated the magnitudes anew, but Ulugh Beg was the first astronomer to produce a star catalogue with positions based on new, independent measurements. He took the magnitudes from al-Sufi (Knobel 1917). Thus his catalogue, published in manuscript in 1437, was new with respect to Ptolemaios both in positions and in magnitudes. A modern translation of the catalogue, based on the Persian manuscripts of the catalogue present in Great Britain, was published by Knobel (1917). The results of an analysis of the positional accuracy of the catalogue of Ulugh Beg, based on comparison with positions from the modern Hipparcos Catalogue, have been published by Heiner Schwan (2002), in a paper that acted as a stimulus for our work on old star catalogues. Shevchenko (1990) separates systematic and random errors in the analysis of the accuracy of the star catalogues of Ptolemaios and Ulugh Beg, for zodiacal stars only. Krisciunas (1993) extends this analysis to all stars in Ulugh Beg.

A machine-readable version of the star catalogue of Ptolemaios has been made available by Jaschek (1987), based on Manitius (1913). In the present paper we provide machine-readable versions of the star catalogue of Ptolemaios, according to the edition of Toomer, and of the star catalogue of Ulugh Beg according to the edition by Knobel. We analyse the accuracy of both catalogues by comparison with the modern Hipparcos

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[*] The full Tables are available in electronic form only at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/

Catalogue. We compare the Knobel and Toomer editions of the star catalogue of Ptolemaios (Appendix A.2).

In the following we refer to (our machine-readable versions of) the catalogues of Ptolemaios and Ulugh Beg as *Ptolemaios* and *UlughBeg*, respectively. Individual entries are numbered in order of appearance, i.e. P 350 is the 350th entry in *Ptolemaios*, U 250 the 250th entry in *UlughBeg*. The sequence number within a constellation is given by a number following the abbreviated constellation name: Aql 5 is the fifth star in Aquila.

2. Description of the catalogues

2.1. The star catalogue of Ptolemaios

The star catalogue of Ptolemaios is organized by constellation, and begins with 21 northern constellations, followed by the 12 zodiacal and 15 southern constellations. To many constellations some stars are added that lie outside the figure ('amorfotos') that defines the constellation (Table 1). The total number of entries is 1028. For each entry, a description is followed by the longitude, latitude and magnitude. The longitude is expressed in zodiacal sign, degrees and fractions of degrees, the latitude with bo[reios] for northern or no[tios] for southern, degrees and fractions of degrees. The fractions in the Greek manuscripts are sometimes composite, e.g. $\frac{5}{6}$ is expressed as $\frac{1}{2}$ $\frac{1}{3}$. In Toomer (1984, 1998) this is converted to a single fraction, e.g. $\frac{5}{6}$. The fractions F are always such that they correspond to an integer number M of minutes, $M = 60F$. Writing the zodiacal sign as Z and the degrees as G, we may write the longitude as

$$\lambda = (Z - 1) \times 30 + G + F \equiv (Z - 1) \times 30 + G + \frac{M}{60} \qquad (1)$$

Writing the degrees and minutes of the latitude as G and M, respectively, we may write the latitude as

$$\beta = \pm(G + F) \equiv \pm(G + \frac{M}{60}); \qquad +/- \text{ for } S = \text{bo/no} \qquad (2)$$

The magnitudes range from 1 to 6, occasionally qualified with m[eizoon] (greater, i.e. brighter) or el[assoon] (less, i.e. fainter). The magnitude of some stars is indicated 'faint' ('amauros'), a nebulous star as nebel[oeides] .

At the end of each constellation the total number of stars, and the numbers of stars for each magnitude are given.

The catalogue contains three repeated entries (Table 2). From the descriptions of the stars it is clear that Ptolemaios was aware of this. In the translation of Toomer (1998): P 147 'The star on the end of the right leg [of Hercules] is the same as the one of the tip of the staff [of Bootes].' P 400 'The star on the tip of the northern horn [of Taurus], which is the same as the one on the right foot of Auriga.' P 1011 'The star in the mouth [of Piscis Austrinus], which is the same as the beginning of the water [i.e. in Aquarius].'"

The epoch given by Ptolemaios for his catalogue is 1 Thoth 885 Nabonassar, which corresponds to 20 July 137 = JD 1771298. He notes in (book VII.3 of) the Almagest that the change in longitude is *1° in about 100 years, or $2\frac{2}{3}°$ in the 265 years between Hipparchos' and our observations* (Toomer, 1998, p.333). Subtraction of 265 Egyptian years of 365 days each then gives the approximate epoch of the measurements by Hipparchos as 1 Thoth 620 Nabonassar, which corresponds to 24 September −128 (=129 B.C.) = JD 1674573.

The positions given in the star catalogue of Ptolemaios show a systematic offset: its longitudes are on average about 1° too

Table 1. Constellations in the catalogue of Ptolemaios

C	abbv	N	N_a	P	C	abbv	N	N_a	P
1	UMi	7	1	1	26	Leo	27	8	462
2	UMa	27	8	9	27	Vir	26	6	497
3	Dra	31	0	44	28	Lib	8	9	529
4	Cep	11	2	75	29	Sco	21	3	546
5	Boo	22	1	88	30	Sgr	31	0	570
6	CrB	8	0	111	31	Cap	28	0	601
7	Her	29	1	119	32	Aqr	42	3	629
8	Lyr	10	0	149	33	Psc	34	4	674
9	Cyg	17	2	159	34	Cet	22	0	712
10	Cas	13	0	178	35	Ori	38	0	734
11	Per	26	3	191	36	Eri	34	0	772
12	Aur	14	0	220	37	Lep	12	0	806
13	Oph	24	5	234	38	CMa	18	11	818
14	Ser	18	0	263	39	CMi	2	0	847
15	Sge	5	0	281	40	Arg	45	0	849
16	Aql	9	6	286	41	Hya	25	2	894
17	Del	10	0	301	42	Crt	7	0	921
18	Equ	4	0	311	43	Crv	7	0	928
19	Peg	20	0	315	44	Cen	37	0	935
20	And	23	0	335	45	Lup	19	0	972
21	Tri	4	0	358	46	Ara	7	0	991
22	Ari	13	5	362	47	CrA	13	0	998
23	Tau	33	11	380	48	PsA	12	6	1011
24	Gem	18	7	424					
25	Cnc	9	4	449		total	920	108	1028

Notes. For each constellation the columns give the sequence number C, the abbreviation for it that we use, the number of stars in the constellation N, the number of associated stars outside the constellation figure N_a, and the sequence number of the first star in the constellation P

Table 2. Repeated entries in *Ptolemaios*

ν^2 Boo P 96 – P 147	β Tau P 230 – P 400	α PsA P 670– P 1011

small. An example is shown in Fig. 1. The difference in longitude due to precession between the epochs of Ptolemaios and Hipparchos, according to modern computation, is about 3°40′, about 1° more than the value given by Ptolemaios. This has led to the suggestion that Ptolemaios did not make independent measurements, but merely copied the catalogue of Hipparchos, applying a (wrong) correction for precession. An alternative explanation is that the zero point of the longitude scale, i.e. the vernal equinox, as used by Ptolemaios is about 1° off, due to errors in his solar theory. Opinion as to which of these two explanations is the correct one have oscillated ever since Tycho Brahe, as reviewed by Grasshoff (1990). The ingeneous statistical analysis by Duke (2003), who compares the positions in Ptolemaios to the times for rising and setting of stars in the *Commentary to Aratus* by Hipparchos, indicates that Ptolemaios indeed copied most of his positions from Hipparchos.

2.2. The star catalogue of Ulugh Beg

This star catalogue is organized as that of Ptolemaios, giving mostly the same stars in the same 48 constellations in the same order (Table 3). There are some differences, however (Table 4). Eleven stars from *Ptolemaios* are absent in *UlughBeg*, including the three repeated entries of *Ptolemaios*; on the other hand, the entry P 657 is split into two stars. As a result, the total number of entries in *UlughBeg* is 1018. Of these, one (U 961) has no coordinates, as its Ptolemaic original (P 964) was not seen by Ulugh Beg. 27 entries were too far south for Ulugh Beg to measure, and
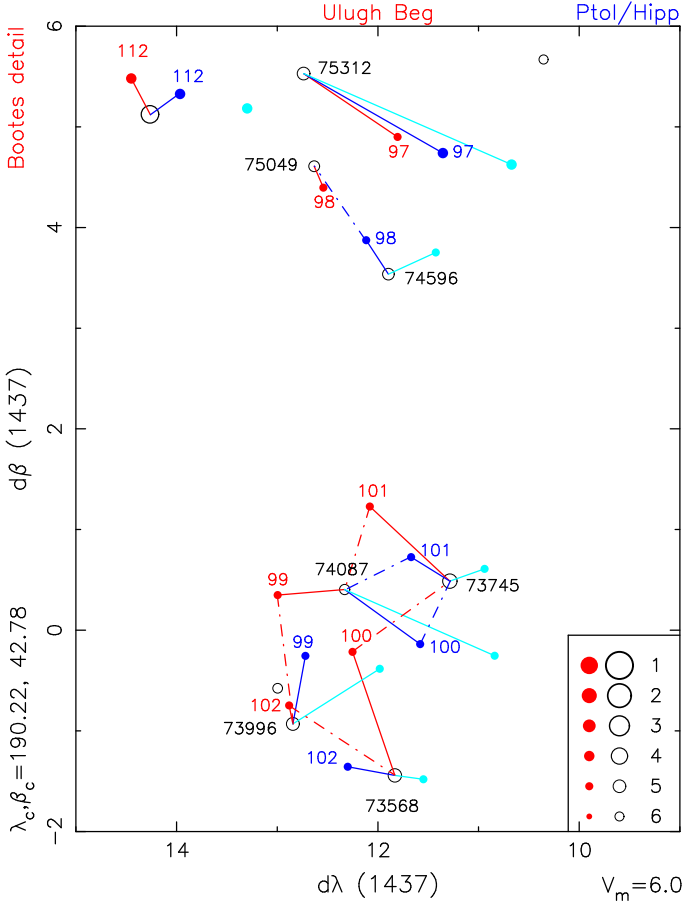
Figure 1. Detail of the constellation Bootes (see Fig. B.5), showing the relative positions of the stars in *UlughBeg* (red), *Ptolemaios* (light blue, epoch 137), and *Ptolemaios* after correction to the epoch of Hipparcos (−128), by subtraction of 2°40′ from the longitude (dark blue). Stars from the modern Hipparcos catalogue are indicated with black open circles. For illustrative purposes, the positions of these stars and of the stars from both epochs of Ptolemaios were converted with modern precession equations to the epoch of Ulugh Beg, 1437. It is seen that the catalogue positions as given by Ptolemaios for 137 are systematically too low. Our identifications are indicated with solid lines; those by Knobel (1917) and Toomer (1998) with dash-dotted lines, when different from our identifications. For the projection used see Sect. B.

Table 3. Constellations in the catalogue of Ulugh Beg

C	abbv	N	N_a	U	C	abbv	N	N_a	U
1	UMi	7	1	1	26	Leo	27	8	459
2	UMa	27	8	9	27	Vir	26	6	494
3	Dra	31	0	44	28	Lib	8	9	526
4	Cep	11	2	75	29	Sco	21	3	543
5	Boo	22	1	88	30	Sgr	31	0	567
6	CrB	8	0	111	31	Cap	28	0	598
7	Her	28	1	119	32	Aqr	42	3	626
8	Lyr	10	0	148	33	Psc	34	4	671
9	Cyg	17	2	158	34	Cet	22	0	709
10	Cas	13	0	177	35	Ori	38	0	731
11	Per	26	3	190	36	Eri	34	0	769
12	Aur	13	0	219	37	Lep	12	0	803
13	Oph	24	5	232	38	CMa	18	11	815
14	Ser	18	0	261	39	CMi	2	0	844
15	Sge	5	0	279	40	Arg	45	0	846
16	Aql	9	6	284	41	Hya	25	2	891
17	Del	10	0	299	42	Crt	7	0	918
18	Equ	4	0	309	43	Crv	7	0	925
19	Peg	20	0	313	44	Cen	37	0	932
20	And	23	0	333	45	Lup	19	0	969
21	Tri	4	0	356	46	Ara	7	0	988
22	Ari	13	5	360	47	CrA	13	0	995
23	Tau	32	11	378	48	PsA	11	0	1008
24	Gem	18	7	421					
25	Cnc	9	4	446		total	916	102	1018

Notes. For each constellation the columns give the sequence number C, the abbreviation for it that we use, the number of stars in the constellation N, the number of associated stars outside the figure of the constellation N_a, and the sequence number of the first star in the constellation U

Table 4. Comparison of entries in *UlughBeg* and *Ptolemaios*

P	U		P	U
P 147*	absent		P 884-889,892,893	copied
P 233	absent		P 961-963,965-971	copied
P 400*	absent		P 964	empty
P 434,435	U 432,431		P 981,982	copied
P 611,612	U 609,608		P 991-997	copied
P 651	absent		P 1011*	absent
P 657	U 653,654		P 1023-1028	absent
P 665,666	U 663,662			

Notes. P 964 and P 982 are annotated by Ulugh Beg with *not seen*. An asterisk indicates a repeat entry in *Ptolemaios*.

for these he took over the positions from al-Sufi, adding 6°59′ to the longitudes to correct for precession; al-Sufi already had added 12°42′ to the longitudes of Ptolemaios to correct for precession (Knobel 1917); the correction to the longitudes between Ulugh Beg and Ptolemaios thus is 19°41′. These 27 entries include one star, U 979 = P 982, which Ulugh Beg remarks he did not see.

The original star catalogue of Ulugh Beg was probably written in Persian, and Knobel (1917) based his edition on the Persian manuscripts available to him. The Knobel edition gives for each entry the sequence number (as in Baily 1843) for the catalogue as a whole, the sequence number within the constellation, a brief description of the star, the modern identification, the longitude in zodiacal sign Z and integer degrees G and minutes M, the latitude in sign S, integer degrees G and minutes M, and the magnitude. The sign of the latitude is often omitted, implicitly assumed to be the same as for the previous entry. The ecliptic longitude is found from

$$\lambda = Z \times 30 + G + \frac{M}{60} \qquad (3)$$

and the latitude from

$$\beta = \pm(G + \frac{M}{60}) \qquad +/- \quad \text{for} \quad S = +/- \qquad (4)$$

Note that the indication of the zodiacal sign in *UlughBeg* differs from that in *Ptolemaios* by one: for example, a star with longitude 10° has Z=1 in *Ptolemaios*, and Z=0 in *UlughBeg*.

The magnitude in *UlughBeg* is an integer, or occasionally indicated as two integers bracketing the actual magnitude. For the modern identifications according to Knobel (1917), see Sect. 3.1.

The epoch given by Ulugh Beg is the beginning of the Islamic year 841, i.e. 5 July 1437 = JD 2246108.

3. Identification procedure

The procedure that we follow for the identification of each star from the catalogues of Ptolemaios and Ulugh Beg is *mutatis mu-*

Table 5. Meaning of flags I classifying our identifications

1	nearest star, secure identification
2	not nearest star, secure identification
3	probable identification, not secure because too far or too faint
4	possible identification other identification(s) also possible
5	not identified
6	repeat entry

Figure 2. Detail of the constellation Orion (see Fig. B.36) in *Ptolemaios* (red) and *UlughBeg* (blue). Stars from the modern Hipparcos catalogue are indicated with black open circles. For comparison purposes the positions of these stars and of stars from *UlughBeg* have been converted to the epoch of Hipparchos/Ptolemaios, with modern precession equations.

tandis identical to the procedure that we followed for the catalogue of Brahe, and we refer to Verbunt & van Gent (2010a) for details. Briefly, we select all stars from the *Hipparcos Catalogue* with a Johnson visual magnitude brighter than 6.0, we correct their equatorial positions for proper motion between the Hipparcos epoch 1991.25 and the epoch of the old catalogue, then precess the resulting equatorial coordinates from the Hipparcos equinox 2000.0 to the equinox of the old catalogue, and finally convert the coordinates from equatorial to ecliptic, using the obliquity appropriate for the old equinox.

For each entry in the old catalogue we find the nearest – in terms of angular separation – counterpart with $V \leq 6.0$ in the Hipparcos Catalogue. In general, this counterpart is selected by us as a secure identification, and given an identification flag 1. If a significantly brighter star is at a marginally larger angular distance, we select that star as the secure counterpart, and give it flag 2. Especially for larger angular distances we may decide that the identification is uncertain (flag 3); and occasionally several Hipparcos stars appear to be comparably plausible as counterparts for the same entry (flag 4). An entry for which we do not find a plausible identification is flagged 5; and an entry which is identified with an Hipparcos star that already is the identification of another entry – i.e. a repeat entry – is flagged 6. This notation is summarized in Table 5.

For *Ptolemaios*, we decided to use the equinox of Hipparchos, JD 1674573 (−128), i.e. we convert both modern and old positions to this equinox: the modern Hipparcos positions as indicated above, and the positions in *Ptolemaios* by subtracting 2°40′ from the longitude. These converted positions are then used in the search for counterparts. For *UlughBeg* we use the equinox JD 2246108 (1437).

In making our identifications we not only look at individual stars, but also at star patterns. Two examples are shown in Fig. 2: the middle of three stars in the sword of Orion in *UlughBeg* is closer to the modern most northern star, but we identify it with the middle modern star; and P 767 is closest to HIP 26563, but since this star is already identified with P 766, we identify P 767 with HIP 25923. Another example is furnished by two stars in Ara in *Ptolemaios*, P 996 and P 997, near −1.5,−4.9 and −5.0,−5.9 in Fig. B.48 (left), respectively. Because all other stars in Ara have identifications to the east (left in the Figure) of the old catalogue position we identify both stars with a star to the east as well, HIP 85258 near 0.4,−3.5 and HIP 83081 near −3.3,−4.4; even though P 996 is closer to HIP 83081 and P 997 closer to HIP 82363 near −3.9,−7.6. Figure B.48 for Ara in *UlughBeg* illustrates also how we prefer brighter, further counterparts to fainter nearby ones. In very crowded constellations, identifications may be made more easily if only brighter modern Hipparcos stars are considered, as may be seen most spectacularly in Argo by comparing Fig. B.42 (limiting magnitude $V=6$) with Fig. B.41 (limiting magnitude $V=5$). Further examples are furnished by the illustrations for *Ptolemaios* and *UlughBeg* for the constellations Centaurus (Fig. B.46) and Ara (Fig. B.48).
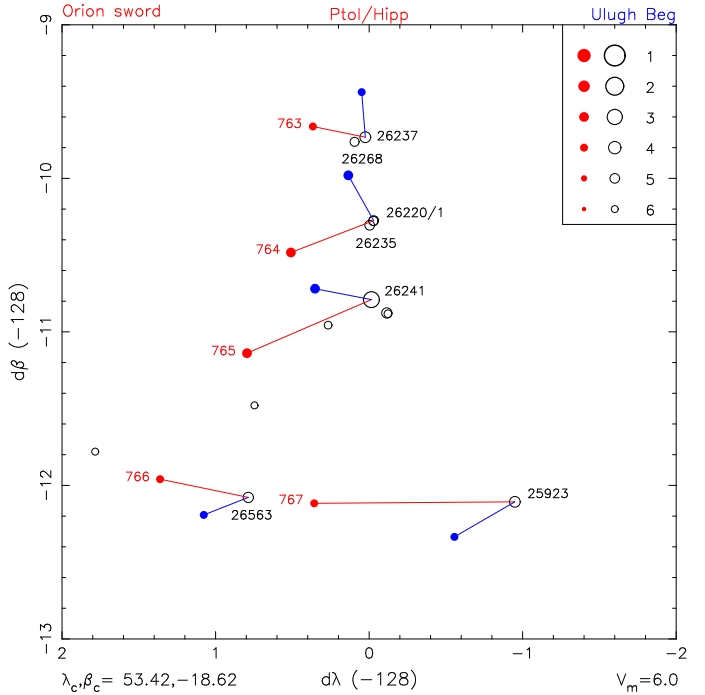
This selection between only bright stars makes us confident that we have often found the correct identification, even in crowded constellations.

Nonetheless, it must be noted that our identification flags are to some extent subjective. For example, P 41 near −14.1,−12.7 in Fig. B.2 (left) is identified by us with HIP 44248 with the flag 'probable', but we might have chosen to leave it unidentified, or even to identify it with the closer HIP 47029, near −10.7,−12.1, the counterpart of the corresponding entry in *UlughBeg*.

The identifications of the stars in the Pleiades gives a further illustration of the ambiguities that occasionally occur (see Fig. 3. P 409, P 411 and P 412 are identified with relative ease, but P 410 is ambiguous: we choose the brighter HIP 17499 as the counterpart, in agreement with the description 'the sourthern end of the advance side', but Toomer (1998) prefers the closer albeit fainter HIP 17608. The descriptions of the stars in the Pleiades by Ulugh Beg is virtually identical to those by Ptolemaios, but the positions differ markedly, which leads us to identify three stars in *UlughBeg* differently from their counterparts in *Ptolemaios*. Thus U 409 is identified to HIP 17702, its counterpart P 412 to HIP 17954. Identification with HIP 17702 (Alcyone) is in accordance with it being the brightest star in the Pleiades, in accordance with the magnitude 4 assigned to U 409/P 412 both in *Ptolemaios* and in *UlughBeg*, which give the three other Pleiades members magnitude 5. Identification with HIP 17954 fits better with the description 'the small star outside the Pleiades towards the North', and Knobel identifies U 409 accordingly.

3.1. Identifications by Toomer and Knobel

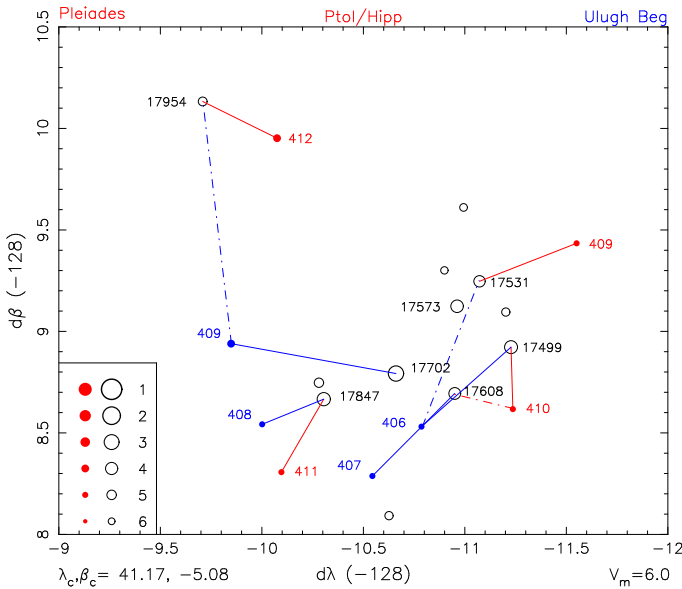Toomer (1998) and Knobel (1917) give Bayer names and/or Flamsteed numbers, and occasionally an HR (Bright Star

Figure 3. Stars in the Pleiades in *Ptolemaios* (red) and *UlughBeg* (blue), together with stars according to the modern Hipparcos Catalogue (open circles). (See Figs. B.23 and B.24.) For comparison purposes the positions of these stars and of stars from *UlughBeg* have been converted to the epoch of Hipparcos/Ptolemaios, with modern precession equations. Solid lines indicate our identifications, dash-dotted lines the identifications by Toomer (1998) and Knobel (1917), when these differ from our identifications.

Catalogue) number, as modern identifications. We convert these to HD numbers through the *Bright Star Catalogue* (Hoffleit & Warren 1991) and the HD numbers to Hipparcos numbers with the modern Hipparcos catalogue (ESA, 1997). For those cases where the Flamsteed number is not given in the *Bright Star Catalogue*, we convert stars from the Hipparcos catalogue to the epoch of Flamsteed, 1690.0 = JD 2338331 and identify the position in the catalogue of Flamsteed (1725) with the nearest Hipparcos match, which is always within 2′.

In a number of cases Knobel gives an identification consisting of a roman and an arabic number; in two cases a zero and a number. These refer to the catalogue of Piazzi (1803; we use the 1814 reprint). To find the corresponding *Hipparcos* numbers we convert the positions of all *Hipparcos* entries brighter than $V = 6.0$ to the equinox of the Piazzi catalogue 1800.0 = JD 2378497 and find the nearest *Hipparcos* entry to each of the Piazzi stars. This leads to an unambiguous identification in all cases with positional differences of about 0.′2 or less.

In a number of cases Knobel gives an identification from Lacaille (Baily 1847). We convert Hipparcos entries to the epoch of this catalogue, JD 2360235, to identify Lacaille numbers with Hipparcos stars. Knobel identifies U 867 with Brisbane 2249. This star is identified in Baily (1847) with Lac. 3580 and we identify it through this with HIP 43603.

In two cases Knobel gives an identification to a star in the edition by Weisse (1846) of observations by Bessel, viz. W.B. 2h788 for U 785 and W.B. 9h439 for U 901, which by converting Hipparcos entries to the epoch of this catalogue, JD 2387628, we identify with HIP 13421 and HIP 46404, respectively.

For one star the only identification given by Knobel is from Hevelius (U 217 = 14H Cam). We convert this to HIP 19949 using our edition of the Hevelius Catalogue (Verbunt & Van Gent 2010b).

4. The machine-readable catalogues

4.1. The star catalogue of Ptolemaios

The machine-readable table *Ptolemaios* contains the following information (see Table 6). The first column gives the sequence number P. The second and third column give the sequence number of the constellation C and the abbreviation of the constellation name. The fourth column gives the sequence number i within the constellation; a star outside the constellation figure is flagged 'a' in column five. Columns 6, 7 and 8 give the ecliptic longitude in zodiacal sign Z, degrees (G) and minutes (M), and columns 9, 10 and 11 the latitude in degrees (G), minutes (M), and sign S. These may be converted to longitude and latitude with Eqs. 1,2, where sign B stands for bo[reios] and A for no[tios]. Column 12 gives the magnitude V according to Ptolemaios, and column 13 the qualifier q, usually blank, but an f or b for fainter or brighter, respectively. The stars indicated by Ptolemaios as 'faint' are written as magnitude 7 in the machine-readable catalogue, and the nebulous stars as 9.

Columns 14-20 provide additional information from our analysis, viz. the Hipparcos number of our identification HIP, the flag I indicating the quality of the identification, the flag T which compares our identification with that by Toomer (see Table 8), the visual (Johnson) magnitude V_H given in the *Hipparcos Catalogue* for our identification, the differences in longitude $\Delta\lambda$ and latitude $\Delta\beta$ in minutes as tabulated, and the angle Δ between the catalogue entry and our Hipparcos identification, in arcminutes (′). If the catalogue entry in degrees as given by *Ptolemaios* is λ, β and the value computed from the position and proper motion in the *Hipparcos Catalogue* $\lambda_{HIP}, \beta_{HIP}$, then columns 18 and 19 give give $60(\lambda_{HIP} - \lambda)$ and $60(\beta_{HIP} - \beta)$.

Column 21 indicates with an asterisk those entries which are annotated in Appendix A.4.

4.2. The star catalogue of Ulugh Beg

The machine-readable table *UlughBeg* contains the following information (see Table 7). The first column gives the sequence number U, the second column a flag u which is set to 'c' when the position of the entry is stated by Ulugh Beg to be derived from the catalogue of Ptolemaios via al-Sufi. Column 3 gives the P number of the corresponding entry in *Ptolemaios*. The fourth and fifth column give the sequence number of the constellation C and the abbreviation of the constellation name. The sixth column gives the sequence number i within the constellation; a star outside the constellation figure is flagged 'a' in column seven. Columns 8, 9 and 10 give the ecliptic longitude in zodiacal sign Z, degrees (G) and minutes (M), and columns 11, 12 and 13 the latitude in degrees (G), minutes (M), and sign S. A These may be converted to longitude and latitude with Eqs. 3,4, where sign B stands for + and A for −, respectively. In our machine-readable catalogue, we follow strictly the convention for Z of (the Knobel edition of) the catalogue of Ulugh Beg, and thereby accept that it differs from the convention in most other ancient catalogues, e.g. that of Ptolemaios, as reflected in the difference between Eqs. 1 and 3. Column 14 gives the magnitude V according to Ulugh Beg / al-Sufi, and column 15 the qualifier q, usually blank, but an f or b for fainter or brighter, respectively. Note that Ulugh Beg (in the Knobel 1917 edition) indicates intermediate magnitude values by giving two integers, either $n - n+1$, which we indicate n f in columns 14, 15; or $n+1 - n$, which we indicate $n+1$ b in columns 14, 15. For example, the magnitude of U 5 is

5

Table 6. The machine-readable catalogue of Ptolemaios

P	C	abb.	i F	Z G M	G M S	V q	HIP	I T	V_H	$\Delta\lambda$	$\Delta\beta$	$\Delta(')$	a
1	1	=UMi	1	3 00 10	66 00 B	3	11767	1 1	2.0	88.8	−9.4	37.4	
2	1	=UMi	2	3 02 30	70 00 B	4	85822	1 1	4.3	108.5	−18.4	41.6	
3	1	=UMi	3	3 10 10	74 20 B	4	82080	1 1	4.2	116.9	−41.5	52.6	
4	1	=UMi	4	3 29 40	75 40 B	4	77055	2 1	4.3	21.9	−48.4	48.7	
5	1	=UMi	5	4 03 40	77 40 B	4	79822	1 1	4.9	−28.7	3.1	6.8	
6	1	=UMi	6	4 17 30	72 50 B	2	72607	1 1	2.1	−101.7	−2.0	30.1	
7	1	=UMi	7	4 26 10	74 50 B	2	75097	2 1	3.0	−136.1	14.5	38.2	
8	1	=UMi	8 a	4 13 00	71 10 B	4	70692	1 1	4.3	−119.5	3.1	38.7	
…													
18	2	=UMa	10	4 11 00	44 00 B	4 f	48402	2 1	4.6	78.4	−358.0	362.8	*

Notes. For explanation of the columns see Sect. 4.1

Table 7. The machine-readable catalogue of Ulugh Beg

U u	P	C	abb.	i F	Z G M	G M S	V q	HIP	I K I_P	V_H	$\Delta\lambda$	$\Delta\beta$	$\Delta(')$	a
1	1	1	=UMi	1	2 20 19	66 27 B	3	11767	1 1 1	2.0	23.4	−24.9	26.7	
2	2	1	=UMi	2	2 22 25	70 00 B	4	85822	1 1 1	4.3	55.8	−7.2	20.4	
3	3	1	=UMi	3	3 00 55	73 45 B	4	82080	1 1 1	4.2	19.6	6.0	8.1	
4	4	1	=UMi	4	3 17 43	75 36 B	4	77055	1 1 1	4.3	102.1	−32.6	41.6	
…														
8	8	1	=UMi	8 a	4 00 55	71 45 B	4	70692	1 1 1	4.3	−30.4	−21.6	23.7	
9	9	2	=UMa	1	3 14 55	40 15 B	4	41704	1 1 1	3.3	13.4	−3.0	10.6	
10	10	2	=UMa	2	3 15 43	43 48 B	5	42080	3 1 1	5.5	−117.7	43.4	94.9	*
…														
21	21	2	=UMa	13	3 25 43	29 00 B	3 f	44471	1 1 1	3.6	21.0	−4.1	18.9	
22	22	2	=UMa	14	3 25 16	36 00 B	5 b	45493	1 1 1	4.8	9.6	2.2	8.1	
…														
881 c	884	40	=Arg	36	4 28 11	69 40 A	4	38827	2 1 1	3.5	−306.0	-41.5	112.5	

Notes. For explanation of the columns see Sect. 4.2

indicated by Knobel as 5–4, which in the machine-readable table is given as 5 b; for U 15 magnitude 4–5 is given as 4 f.

Columns 16-23 provide additional information from our analysis, viz. the Hipparcos number of our identification HIP, the flag I indicating the quality of the identification, the flags K which compares our identification with that by Knobel and I_P which indicates whether the corresponding entries in *UlughBeg* and *Ptolemaios* have the same Hipparcos counterpart (see Table 9), the visual (Johnson) magnitude V_H given in the *Hipparcos Catalogue* for our identification, the differences in longitude $\Delta\lambda$ and latitude $\Delta\beta$ in minutes as tabulated, and the angle Δ between the catalogue entry and our Hipparcos identification, in arcminutes ('). If the catalogue entry in degrees as given by Ulugh Beg is λ, β and the value computed from the position and proper motion in the *Hipparcos Catalogue* $\lambda_{HIP}, \beta_{HIP}$, then columns 21 and 22 give $60(\lambda_{HIP} - \lambda)$ and $60(\beta_{HIP} - \beta)$.

Column 24 indicates with an asterisk those entries which are annotated in Appendix A.5

5. Results

5.1. Ptolemaios

It is indicative of the high quality of the (reconstructed) catalogue of Ptolemaios that the number of identifications we consider secure (flags 1-2) is 1009, not counting the 3 repeat entries. For 15 entries we have a probable counterpart, and only one entry we leave unidentified. The large agreement between our identifications and those of Toomer (1998) for *Ptolemaios* as seen in Table 8 also suggests that most identifications may be considered secure. The cases where we disagree with the

Table 8. Frequency of flags T of identifications by Toomer (1998) as a function of our flags I.

I\T	0	1	2	3	all
1	0	807	2	23	832
2	1	168	1	7	177
3	0	2	1	11	14
4	0	0	1	0	1
5	0	0	0	1	1
6	0	2	1	0	3
all	1	979	6	42	1028

Notes. The meanings of flags *I* are explained in Sect. 3, those of flags *T* are as follows: 0 unidentified in Toomer (1998), 1 Toomer gives same identification as we do, 2 Toomer choses one of two plausible identifications and we the other, 3 we reject the identification given by Toomer.

identification by Toomer (1998) usually arise when he prefers a fainter star (see for example the annotations with P 98, P 132 and P 152 in Sect. A.4). Occasionally the descriptions of the stars in *Ptolemaios* do not match the positions, and if followed may lead to a different identification, as for P 410 in the Pleiades (Fig. 3), or to a permutation of identifications, as for P 100 and P 101 in Bootes (Fig. 1).

Figure 4 shows that the correlation between the magnitudes as given by Ptolemaios and the magnitudes from modern measurements is good. Note that in this figure we ignore the qualifiers fainter and brighter made to some magnitudes (q in Table 6). Remarkably, the 11 stars indicated by Ptolemaios as 'faint' are not fainter than those given magnitudes 5 or 6 by him. The errors $\Delta\lambda$ in longitude and $\Delta\beta$ latitude show systematic trends with longitude and latitude. The errors $\Delta\lambda$ and $\Delta\beta$ are not correlated;

Table 9. Frequency of flags K of identifications by Knobel (1917) and I_P of identification in *Ptolemaios* as a function of our flags I.

I	flag Knobel					flag Ptolemaios				
	0	1	2	3	all	0	1	2	3	all
1	0	858	3	9	870	1	826	6	37	870
2	0	121	0	8	129	0	121	0	8	129
3	0	10	0	1	11	0	9	0	2	11
4	0	0	3	1	4	0	0	4	0	4
5	0	0	0	3	3	0	0	0	3	3
6	0	0	0	0	0	0	0	0	0	0
all	0	989	6	22	1017	1	956	10	50	1017

Notes. The meanings of flags *I* are explained in Sect. 3. Those of flags *K*/I_P are as follows: 0 unidentified in Knobel/*Ptolemaios*, 1 Toomer/*Ptolemaios* gives the same identification as we do, 2 Knobel/*Ptolemaios* choses one of two plausible identifications and we the other, 3 the identification is different from that given by Knobel/*Ptolemaios*. U 961, which has no coordinates, is excluded.

the spread in errors at each λ is slightly larger for $\Delta\lambda$ than for $\Delta\beta$.

Using maximum likelihood (i.e. Poisson statistics), we fit gaussians to the histograms of the errors for all errors in the range $-100'$ to $+100'$ (and a more limited range $-50'$ and $+50'$), and find an offset of about $7'$ ($9'$) and a width $\sigma = 30'$ ($27'$) for $\Delta\lambda$; and an offset of $-0.7'$ ($+0.3'$) and a width $\sigma = 29'$ ($23'$) for $\Delta\beta$. These widths are slightly larger than those found by Shevchenko (1990, for zodiacal stars only) and by Schwan (2002), who subtracted the systematic trends in the errors before fitting gaussians to the remaining spread. (Shevchenko gives rms-errors, excluding outliers from the computations; the article by Schwan, written for a semi-popular journal, gives no details on his determination of σ.) The total error Δ peaks between $20'$ and $30'$; the errors Δ increase only slowly with magnitude.

5.2. UlughBeg

We have securely identified 999 entries in *UlughBeg* and tentatively another 15 entries; 3 entries we leave unidentified (Table 9). In 989 cases our identification agrees with that by Knobel (1917), in 6 cases we consider the identification by Knobel plausible even if different from ours, and in 22 cases we think our identification is better. The constellation Bootes provides an example where the identifications by Knobel (1917) are a permutation of our preferred identifications (Fig. 1). The Pleiades illustrate some other differences (Fig. 3): Knobel identifies U 409 with the stars that we choose for the corresponding entry P 412 in *Ptolemaios*; because Ulugh Beg places U 409 almost a degree further south than Ptolemaios does P 412, we prefer a different counterpart. These examples imply that the numbers given in Table 9 should be considered as approximate rather than exact.

Figure 5 shows that the magnitudes assigned by Ulugh Beg correlate well with the modern Hipparcos measurements; his faintest magnitude 6 slightly underestimates the actual brightness. Note that in the figure we ignore the qualifiers fainter and brighter for the magnitudes. The errors $\Delta\lambda$ in longitude show a trend with longitude similar to that in Ptolemaios, with a maximum at the largest distance from the vernal equinox, i.e. near the autumnal equinox. Due to an overall offset, however, the absolute value of the errors are actually smallest near the autumnal equinox and largest near the vernal equinox; this is in contrast to the situation in Ptolemaios. The errors $\Delta\beta$ in latitude show a smaller correlation with longitude. The errors in longi-
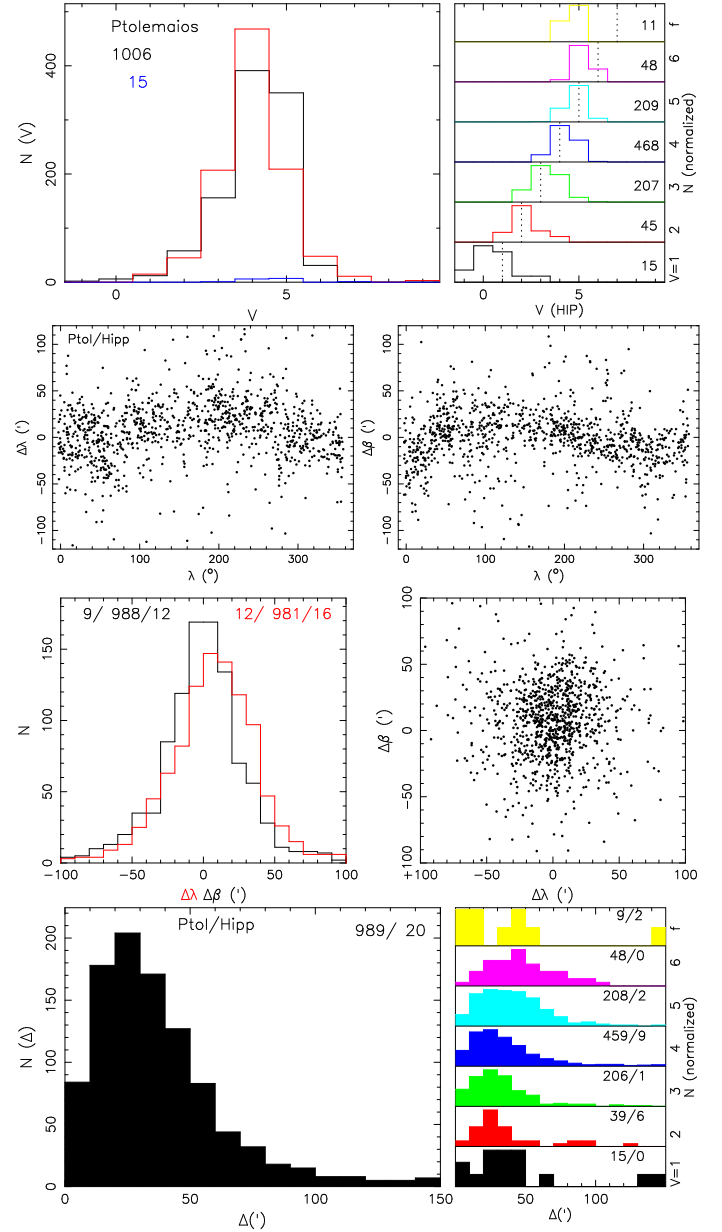
Figure 4. Magnitude and position errors and their correlations of *Ptolemaios*. The top graph shows the distributions of magnitudes according to Ptolemaios (7=faint, 9=nebulous) for securely identified stars (identification flags $I - 1, 2$, red), for not securely identified stars (flags 3,4, blue), and of the magnitudes in the Hipparcos catalogue for all secure identifications (black) in the large frame, and for each magnitude according to Ptolemaios in the small frames. The middle frames show the errors in longitude and latitude as a function of longitude and of one another, and histograms of the position errors of the securely identified stars separately for the longitude (red) and latitude (black). The numbers indicate stars within the frame (middle) and outside the frame to the left or right. The lower frame shows the distribution of the position angles Δ, for all securely identified entries in the large frame, of for each magnitude according to Ptolemaios separately in the small frames. The numbers indicate the number of entries within/outside the frame.

tude and latitude are not correlated. Using maximum likelihood, we fit gaussians to the histograms of the errors for all errors in the range $-100'$ to $+100'$, and find an offset of about $-10'$ for $\Delta\lambda$ and $\sigma \simeq 26'$; and for $\Delta\beta$ an offset of about $7'$ and $\sigma \simeq 21'$. Limiting the fits to errors with absolute values less than about

Figure 5. Magnitude and position errors and their correlations of *UlughBeg*. As Figure 4, now for *UlughBeg*.

Table 10. Correlation of magnitudes by Ulugh Beg / al-Sufi with those by Ptolemaios

	1	2	3	4	5	6	7	9
1	15	0	0	0	0	0	0	0
2	0	32	3	0	0	0	0	0
3	0	10	178	13	0	0	0	0
4	0	3	20	394	6	0	2	1
5	0	0	2	61	184	3	6	0
6	0	0	1	4	25	45	4	0
8	0	0	0	0	1	0	0	0
9	0	0	0	0	0	0	0	4

Notes. In the machine-readable tables magnitude 7 refers to stars called faint by Ptolemaios; magnitude 8 refers to the entry for which Ulugh Beg remarks 'no star is visible in that location'; magnitude 9 to entries called nebulous.

5.3. Comparison of Ptolemaios and Ulugh Beg

Since Ulugh Beg chose to observe the same stars that Ptolemaios lists in his catalogue, one expects a large agreement between the identifications we have produced for corresponding pairs. Table 9 shows that in 956 cases the identifications for the corresponding pairs are identical; and in 10 cases we consider identical identifications possible but prefer different ones. In 50 cases we think the star observed by Ulugh Beg is different from the corresponding entry in *Ptolemaios*. This may be based on a different position, as is illustrated by the pair P 98/U 98 (Fig. 1), or the pairs P 409/U 406 and P 412/U 409 (Fig. 3).

The magnitudes assigned by al-Sufi correlate very well with those assigned by Ptolemaios, as illustrated in Table 10. Stars called faint by Ptolemaios, which have magnitude 7 in the machine-readable table, are distributed around magnitude 5 by Ulugh Beg, which confirms our conclusion based on Figure 4 that the term faint in Ptolemaios refers to his magnitudes 5 and 6. There are ten cases where the magnitude as given by al-Sufi differs by two or more from that in Ptolemaios. In two cases, P 289/U 287 and P 634/U 631, our identifications indicate that al-Sufi referred to a different star than Ptolemaios; in seven cases the fainter magnitude given by al-Sufi corresponds better to the actual magnitude; in one case, P 989/U 986, the brighter magnitude given by Ptolemaios corresponds better to the actual magnitude.

All four nebulous stars in *UlughBeg* correspond to one of the five nebulous stars in *Ptolemaios*. P 567, near 12.3,−4.5 in Fig. B.30, is nebulous in *Ptolemaios*, but the corresponding entry in *UlughBeg* U 564 has magnitude 4–5 (4f). The nebulous entries common to *Ptolemaios* and *UlughBeg* are the open clusters h Per (P 191, U 190), and Praesepe (P 449, U 446), the close pair $\nu^{1,2}$ Sgr (P 577, U 574) and λ Ori (P 734, U 731, Fig. 7). The globular cluster ω Cen (P 955, U 952) is present in both catalogues, but was not recognised as a nebulous object.

Our analysis of the positional errors in Sections 5.1 and 5.2 show that the catalogue of Ulugh Beg is more accurate than the catalogue of Ptolemaios, and thus confirm that his measurements are largely independent.

5.4. Non-stellar sources and double stars

We identify two entries in *Ptolemaios* with open clusters: P 191 with h Per, or possibly with the pair h and χ Per (Fig. B.11), and P 449 with Praesepe in Cancer (Fig. B.26); and we identify one entry with a globular cluster: P 955 with ω Cen (Fig. B.46). P 955

50′ we find the same offsets, but σ's reduced to 22′ for $\Delta\lambda$ and 18′ for $\Delta\beta$. These latter widths are comparable to those given by Shevchenko (1990, for zodiacal stars only), by Krisciunas (1993) and by Schwan (2002); their subtraction of the systematic trends with longitude in the errors has only a small effect. The total error peaks between 10′ and 20′.

Krisciunas (1993) assumes that Ulugh Beg used the same principal reference stars, Spica and Regulus, as Ptolemaios, to explain that the errors in longitude as smallest near the autumnal equinox. However, our analysis shows that the longitude errors of Ptolemaios are smallest near the vernal equinox (Fig. 4). The difference is affected by the different overall offsets of the longitudes (+7′ in Ptolemaios and −11′ in Ulugh Beg). Clearly, the correct interpretation of the trend in the longitude errors depends on a correct understanding of the overall offset.

Figure 6. Detail of Scorpius (see Fig. B.30) showing the relative positions of P 559 and P 560 (red) and the open cluster NGC 6231 (black □), together with the double star HIP 82729 / HIP 82671 (open circles). A red circle marked 559' denotes the position of P 559 when its latitude is corrected from −18° to −19°. HIP 82729 is a high-proper-motion star: the black ● shows the position one would find for −128 if proper motion is ignored. Solid lines indicate our identifications, the dash-dotted lines those by Ashworth (1981).

is given magnitude 5 by Ptolemaios, P 191 and P 449 are indicated as nebulous.

The third object indicated nebulous is P 567, in Scorpius. On the basis of the description of P 567 by Ptolemaios *the nebulous star to the rear of the sting* (translation Toomer), Kunitzsch (1974b) argued that this entry corresponds to the open cluster M 7. Ashworth (1981) repeats this suggestion. The position of P 567 is about 3° from M 7, rather further than the offsets of other identifications in Scorpius (Fig. B.30), which leads us to agree with earlier authors and prefer HIP 87261 as the counterpart.

Ashworth (1981) also makes the interesting suggestion that Ptolemaios may have catalogued NGC 6231. Of the two stars in the third joint of Scorpius the one with the more northern coordinates is called south of the other, and vice versa. Toomer (1998) keeps the descriptions for P 559 and P 560, and switches the coordinates so that P 559 is the northern star both according to position and to description. We follow him in identifying P 559 and P 560 with HIP 82729 and HIP 82671, respectively. However, the positions shown in Fig. 6 suggest that an identification of P 559 with NGC 6231 and P 560 with HIP 82729 is also possible. Ashworth does not switch the coordinates, but emends the latitude of P 559 from −18° to −19°. We denote the star with the emended position P 559', and show its position in Fig. 6. Ashworth (1981) identifies P 560 with NGC 6231 and P 559' with the pair HIP 82729 + HIP 82671 ($\zeta^{2,1}$ Sco). We note that the angular separation between these two stars was 13.'6 in −128 compared to only 6.'5 today, as shown in Fig. 6, and consider the pair HIP 82729 + HIP 82671 an excellent match for P 559' and P 560.

P 577 is described by Ptolemaios as 'the nebulous and double (διπλοῦς) star at the eye [of Sagittarius]'; it corresponds to HIP 92761 (*V*=4.86) and HIP 92845 (*V*=5.00), separated by 12.'2 in −128. P 734 is also described as nebulous by Ptolemaios; it corresponds to HIP 26207, and it is not clear why Ptolemaios would call it nebulous, as the nearest star, HIP 26215, is 18.'5 from HIP 26207 and is rather faint (*V*=5.6, see Fig. 7).

It is interesting to see which close pairs of stars were noted by Ptolemaios as double, and which ones were not. Another entry explicitly denoted as corresponding to two stars is P 150, truely remarkable as the corresponding pair HIP 91919 / HIP 91926
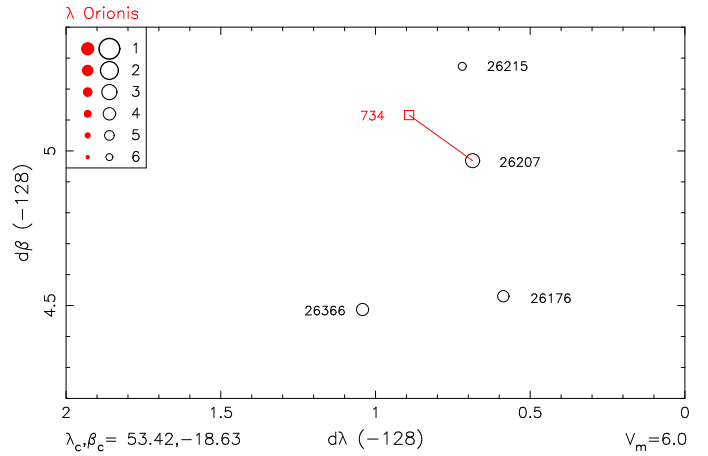
Figure 7. Detail of Orion (see Fig. B.36) showing the positions of P 734 (red) and various stars from the modern Hipparcos catalogue (open circles).

($\epsilon^{1,2}$ Lyr) was separated by only 3.'2 in −128, and the stars are not very bright at *V*=4.46 and 4.59, respectively. In contrast, the pair HIP 72603 / HIP 72622 ($\alpha^{1,2}$ Lib) is not denoted as double by Ptolemaios, perhaps because of its even smaller separation (2.'9) or because of the larger brightness contrast (*V*=5.15 and 2.75). P 601 corresponds to the pair HIP 100027 / HIP 100064 ($\alpha^{1,2}$ Cap) is also not denoted as double by Ptolemaios, even though the pair is bright (*V*=4.30 and 3.58) and well separated (5.'1).

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Appendix A: Emendations and annotations

A.1. Emendations to Toomer

P 138 – P 140. Toomer (1998) in his corrigenda on p. xii cites Kunitzsch (1986) to identify P 138 – P 140 with 77(x) Her, 82(y) Her and 88(z) Her. 88(z) Her = HIP 87280 has V=6.8, too faint for a plausible counterpart. We emend the identifications to 74 Her for P 138, 77(x) Her for P 139, and 82(y) Her for P 140, in agreement with Kunitzsch (1986).

P 166: identification ι Cyg emended to ι^2 Cyg.

P 332: identification π Peg emended tp π^2 Peg.

P 371: identification τ Ari emended to τ^2 Ari.

P 404: identification ω Tau emended to ω^2 Tau.

P 456: identification μ Cnc emended to μ^2 Cnc.

P 458: identification π Cnc emended to π^2 Cnc.

P 570: identification γ Sgr emended to γ^2 Sgr.

P 647: identification τ Aqr emended to τ^2 Aqr.

P 749: identification ψ Ori emended to ψ^2 Ori.

P 910: identification ϕ Hya emended to ϕ^3 Hya.

A.2. Emendations to Manitius; comparison of editions by Manitius and Toomer

Having completed our machine-readable catalogue of Ptolemaios according to the edition by Toomer (1998), we may compare it with the (machine-readable version of the) edition by Manitius (1913), as made available by Jaschek (1987). We compare the longitude, latitude and magnitude of each entry. In a number of cases, the difference we obtain is due to a difference between Jaschek (1987) and the Manitius edition by Neugebauer (1963). Some are due to differences between Neugebauer and Manitius, some due to differences between Jaschek and Manitius, as follows:

P	star		Man.	Jas.	Neu.	Toom.
305	Del 5	β	33 50	33 00	33 50	33 50
501	Vir 5	β	00 20	00 20	00 10	00 10
505	Vir 9	λ	171 00	161 00	171 00	171 00
703	Psc 30	λ	356 20	256 20	356 20	356 20
918	Hya 25	β	−13 40	−13 40	−17 40	−17 40

We emend Jaschek (1987) to agree with Manitius (1913), and emend in both the latitude of P 918. Table A.1 gives the differences that remain, between the Manitius (1913) and Toomer (1998) editions of the star catalogue of Ptolemaios. Positions in

Table A.1. Differences between the Manitius (1913) edition and the machine-readable table *Ptolemaios*.

P	ΔM_λ	ΔM_β	HIP$_{Man}$	P	ΔM_λ	ΔM_β	HIP$_{Man}$
3	350	0		518	0	-20	
42	0	160	46952	569	-240	0	80473
61	0	240		596	-180	0	
69	-160	0		641	0	10	109857
129	0	-150		642	0	-10	
233	0	340	27949	645	0	-30	
268	180	0		667	0	-35	
347	10	0		668	0	35	
348	-10	0		822	-240	0	
366	20	20		852	0	-10	
375	0	30		855	0	-15	
389	-160	0		922	0	10	
395	20	0		931	-10	0	
448	140	0	40167	933	0	5	
501	0	10		954	0	-160	68523
502	0	20		958	0	-160	59449
504	0	-20	63414	961	-10	0	25

Notes. ΔM_λ and ΔM_β give $60(\lambda_{Manitius}-\lambda_{Toomer})$ and $60(\beta_{Manitius}-\beta_{Toomer})$, respectively; the identification by Manitius is indicated only when different from our identification.

Manitius that are very different from those in Toomer are indicated in the Figures in Sect. B in brown.

The magnitudes are identical in both catalogues, with the exception of the magnitude of P 568: 5b in Toomer, 5 in Manitius.

A.3. Annotations to Knobel

In many cases Knobel identifies a catalogue entry with a close pair of stars. If the pair can be separated with the naked eye, we choose the brightest of the pair as identification.

U 879 is identified by Knobel as [Piazzi] VII 235, P Pup. These are two different stars: HIP 38020 and HIP 38164, respectively. The latter is the correct identification.

U 882 is identified by Knobel as o Pup; we amend to o Vel.

A.4. Annotations to individual identifications in Ptolemaios

P 17-18, near −13.6,6.9 and −11.8,8.5 in Fig. B.2 respectively, are described by Ptolemaios as the northern and southern one of the pair in the breast of the Bear. This implies a position for P 18 further south than the catalogue value, and Toomer identifies it with HIP 48402, near −11.9,2.5, which implies an error of 6°. We follow him (and earlier authors) in doing so.

P 36, near 22.2,6.9 in Fig. B.2, corresponds to the combined light of the close (1′.9) pair HIP 63121, HIP 63125.

P 41, near −14.1,−12.7 in Fig. B.2, is equally far removed from HIP 47029, near −10.7,−12.1, to the east and HIP 44248 to the west; we choose the latter, slightly brighter star; Toomer mentions the former as an uncertain possibility.

P 60, near 5.1,15.8 in Fig. B.3 is the combined light of the close (38′′.5) pair HIP 86614/HIP 86620.

P 96, near 7.8,15.4 in Fig. B.5, is almost at the same distance to HIP 75973 and HIP 76041 (V=5.04 and 4.98, d=18′.0 and 17′.3, respectively). We choose the marginally brighter and closer star, Toomer prefers the other.

P 98, near 12.5,4.3 in Fig. B.5 is identified by Toomer with HIP 75049, near 13.0,5.0; we prefer the nearer, brighter star.

P 100-101, near 12.0,0.2 and 12.1,1.1, respectively in Fig. B.5: the identification of P 100 by Toomer is our identification for P 101 and vice versa.

P 132, near 3.1,3.9 in Fig. B.7, is identified by Toomer with a closer ($d=26.'6$) but rather fainter ($V=6.2$) star.

P 150, near −2.0,4.0 in Fig. B.8, the combined light of the close (3.'2) pair HIP 91926 and HIP 191919. Remarkably, Ptolemaios notes that this entry corresponds to two stars, i.e. he was able to see them separately.

P 151, near −2.1,2.4 in Fig. B.8, combined light of the close (50.'1) pair HIP 91971 and HIP 91973

P 152, near −0.5,1.3 in Fig. B.8, is identified by Toomer with the nearest star HIP 92728, but we prefer the brighter star next to it.

P 159, near −12.9,−8.0 in Fig. B.9, is the combined light of the close (19.''9) pair HIP 95947/HIP 95951.

P 191, near −6.7,14.8 in Fig. B.11, is the open cluster h Per. The center of this cluster is $\alpha = 34.°8425, \delta = 57.°15$ (J2000.0, Slesnick et al. 2002).

P 409-411, the Pleiades. Our identifications are based on the description by Ptolemaios as *the northern end of the advance side* (P 409), *the southern end of the advance side* (P 410), and *the rearmost and narrowest end of the Pleiades* (P 411). (Translation by Toomer, who has the same identification for P 409 and P 411; but prefers HIP 17608 for P 410; see Fig. 3).

P 494-496, in the north-east part of Fig. B.27 are identified with help of their descriptions: *the northernmost of the nebulous mass between the edges of Leo and Ursa, called Coma, the most advanced of the southern outrunners of Coma*, and *the rearmost of them, shaped like an ivy leaf* (translation by Toomer).

P 529, near −7.6,0.9 in Fig. B.29, is identified with the close (2.'9) pair HIP 72622/HIP 72603 ($V=2.75/5.15$).

P 541, near 5.0,0.5 in Fig. B.29, is identified by Toomer with HIP 76628; our counterpart is closer and brighter.

P 542, near 5.5,−1.3 in Fig. B.29, is identified by Toomer with the nearest star HIP 76569; we prefer the brighter but rather further HIP 76742.

P 567, near 12.3,−4.5 in Fig. B.30, is called nebulous by Ptolemaios. Toomer suggests that this is due to the proximity of NGC 6441. We consider this unlikely, as this globular cluster has integrated magnitude $V=7.15$. See also the discussion in Sect. 5.4.

P 584, near 8.5,13.5 in Fig. B.31, is identified by us with the nearest star, by Toomer with the marginally brighter star just beyond it, HIP 96950.

P 585, near 12.3,13.8 in Fig. B.31, is identified with Toomer with HIP 98258 ($V=5.0, d=124.'8$), a plausible alternative to our closer but fainter counterpart.

P 588, near 7.7,5.3 in Fig. B.31, is identified by Toomer with the combined light of HIP 96406/HIP 96465. As the distance between these two stars was 12.'2 in 139 BC (it is now 13.'3) we prefer to identify with the brighter star only.

P 601, near −9.4,7.6 in Fig. B.32, is identified by Toomer with the close (5.'1) pair HIP 100027/HIP 100064 ($\alpha^{1,2}$ Cap). There is no hint in Ptolemaios that he noticed a pair, rather than a single star.

P 604, near −11.6,8.3 in Fig. B.32, is identified by Toomer with the close (7.'2) pair HIP 99529/HIP 99572 ($\xi^{1,2}$ Cap). There is no hint in Ptolemaios that he noticed a pair, rather than a single star; ξ^1 Cap at $V=6.3$ is barely visible to the naked eye.

P 661, near 13.9,−11.7 in Fig. B.33, is identified by Toomer with the (10.'1) pair HIP 116901/HIP 116889 (103/104 Aqr; $V=4.8/5.4$). There is no hint in Ptolemaios that he noticed a pair, rather than a single star. We identify with the brightest of the two.

P 786, P 787, P 788, near −9.0,14.1, −11.1,14.3 and −12.6,14.2 in Fig. B.37 respectively. Toomer identifies P 786 with the pair HIP 14923/HIP 14168 ($\rho^{3,2}$ Eri), and P 787 with HIP 13701 (η Eri), and thereby is forced to identify P 788 with the very faint ($V=6.3$) star HIP 13421. We prefer to identify P 786 with ρ^3 Eri, P 787 with ρ^2 Eri, and P 788 with η Eri. The separation between ρ^3 Eri and ρ^2 Eri is 22.'4.

P 955, near −6.8,1.7 in Fig. B.46, is the globular cluster ω Cen. We take the modern position of this cluster from Harris (1996, version of February 2003).

P 1000, near 0.1,−4.2 in Fig. B.49, is identified by Toomer with HIP 92953, near 0.9,−0.7. This implies that the latitude of this source, $\beta = −23°$ ($\kappa\gamma$ in Greek) is erroneous for $\beta = −20°20'$, ($\kappa\gamma'$ in Greek) and better fits the description *to the rear of this* (sc. the previous star).

P 1017, near 8.3,3.2 in Fig. B.50, is identified by Toomer with HIP 111138, which we consider too faint, at $V=6.4$.

A.5. Annotations to individual identifications in UlughBeg

U 10, U 11, near −21.2,10.4 in Fig. B.2. We identify this pair with the two brightest nearby Hipparcos stars.

U 36, near 21.8,6.9 in Fig. B.2, combines the light of the close (44'') pair HIP 63125/63121.

U 60, near 5.8,17.6 in Fig. B.3, combines the light of the close (31.''4) pair HIP 86614/86620.

U 96, near 7.8,15.0 in Fig. B.5, is identified by Knobel with HIP 75973 = ν^1 Boo, further and (marginally) fainter (17.'1, $V=5.0$) than our counterpart, ν^2 Boo.

U 98 is identified differently in *Ptolemaios*, due to a slight shift in position; see Fig. 1.

U 99-U 102, see Fig. 1, are identified with the same four stars in *Ptolemaios* and *UlughBeg*, but in a permutation:

	Ptolemaios	*UlughBeg*	Knobel
U 99	73996	74087	73996
U 100	74087	73568	73745
U 101	73745	73745	74087
U 102	73568	73996	73568

where we also add the identifications of the stars in the catalogue of Ulugh Beg according to Knobel.

U 158, near −12.5,−7.4 in Fig. B.9, corresponds to the combined light of HIP 95947 and HIP 95951 ($\beta^{1,2}$ Cyg).

U 172, near 3.3,5.1 in Fig. B.9. HIP 99639 is only 5.'7 from our counterpart HIP 99675, and Knobel assigns the combined light of these two stars as the counterpart for U 172.

U 174, near 7.7,6.9 in Fig. B.9, is identified by us with the nearest star, but may also be identified with HIP 101138, brighter but further (V=4.9, $d=102.'2$), the counterpart of the corresponding star in *Ptolemaios*, P 175. Knobel identifies U 174 with HIP 101138.

U 183, near 9.6,0.8 in Fig. B.10. An alternative counterpart is HIP 9312, slightly brighter, but further (V=5.3, $d=98.'1$) than our counterpart. Knobel identifies U 183 with HIP 11569 (ι Cas), near 11.6,2.5. HIP 9312 is our counterpart to the corresponding star in *Ptolemaios*, P 184.

U 190: see note with P 191.

U 226 leads **U 227**, i.e. has a smaller longitude, and we identify these entries accordingly, with HIP 23453 and HIP 23767. The pair is near −4.5,0.1 in Fig. B.12. In the corresponding pair in *Ptolemaios*, P 227 trails P 228, and they are identified accordingly with HIP 23767 and HIP 23453, respectively. Knobel identifies U 226 with HIP 23767 and U 227 with HIP 23453.

U 278, near 25.2,4.7 in Fig. B.15, is the combined light of the close (15.''5) pair HIP 92946 and HIP 92951.

U 287, near 5.2,3.7 in Fig. B.16, is south of U 286, just next to it. In *Ptolemaios*, the corresponding P 289 is north of P 288, and the identification differs accordingly (Fig. B.16).

U 370, near 2.3,−2.3 in Fig. B.22, is identified by Knobel with the pair HIP 13654, HIP 13702 ($\rho^{2,3}$ Ari), which is also the identification of the corresponding star in *Ptolemaios*, P 372. We agree with this possibility, but slightly prefer the further but somewhat brighter HIP 13165 (π Ari), in view of the offsets of other identifications near it.

U 406, in Fig. 3, is identified by Knobel with HIP 17531 (Taygeta), the counterpart of the corresponding star in *Ptolemaios*, P 409.

U 409, in Fig. 3, is identified by Knobel with HIP 17954, in accordance with the description in the catalogue *an exterior and small star of the Pleiades*, and with the counterpart of the corresponding star in *Ptolemaios*, P 412. However, its different position in *UlughBeg*, and its magnitude of 4 in the catalogue, lead us to prefer Alcyone as the counterpart.

U 414 and **U 415**, near 15,−1 in Fig. B.23, have different identifications than their counterparts in *Ptolemaios*, P 417, P 418, due to different positions. The counterpart of P 418 is that of U 414.

U 429, near 4.7,5.5 in Fig. B.25, has a very different latitude than its counterpart in *Ptolemaios*, P 431, and accordingly a different counterpart.

U 442, U 443 and **U 444**, near 11.7,−1.6, 10.0,−3.3 and 8.5,−4.5 in Fig. B.25 are shifted in longitude with respect to their counterparts in *Ptolemaios*, P 445-447, such that the counterpart of P 445 is that of U 443 and that of P 446 that of U 444.

U 446 is Praesepe; the distance given in the catalogue is to ϵ Cnc.

U 455, near 3.4,−2.1 in Fig. B.26, corresponds to P 458 in *Ptolemaios*, which has a position closer to HIP 45410, and is identified accordingly in *Ptolemaios*.

U 492, U 493: Knobel's identifications are ambiguous between 7 Leo and 23 Leo or 7 Com and 23 Com; Com agrees with our identifications.

U 512, U 513, near 11.6,−5.2 and 8.9,−6.7 in Fig. B.28. P 516 has the same counterpart as U 512, but P 515 is identified with HIP 65581, near 7.4,−7.1, so that the pair P 515, P 516 is shifted with respect to the corresponding pair U 512, U 513.

U 592, near 10.1,−5.5 in Fig. B.31, is identified by Knobel with the pair HIP 100469, HIP 100591 ($\kappa^{1,2}$ Sgr) near 12.4,−14.2, which must be wrong.

U 653 and **U 654**, near 12.8,−1.5 in Fig. B.33: these two stars correspond to a single entry in *Ptolemaios*, P 657. The entry P 651 has no counterpart in *UlughBeg*.

U 655, near 10.9,−5.8 in Fig. B.33, corresponds to the close (2′.4) pair HIP 115125/6.

U 656, U 657, near 15,−8.3 in Fig. B.33, are identified by us with HIP 116971 and HIP 116758, respectively, i.e. we preserve the north-south ordering. Knobel preserves the ordering in longitude, and thus identifies U 656 with HIP 116758 and U 657 with HIP 116971. The corresponding stars in *Ptolemaios*, P 659 and P 660, are identified with HIP 116758 and HIP 116971, respectively. Our identification of the pair therefore implies that their ordering is switched in *UlughBeg* with respect to *Ptolemaios*.

U 660, near 15.1,−12.6 in Fig. B.33, is identified by Knobel with HIP 117218, near 14.1,−12.6.

U 684, near 11.0,−7.8 in Fig. B.34, is identified by Knobel with HIP 5346, the counterpart of the corresponding star in *Ptolemaios*, P 687.

U 713, near 13.8,9.0 in Fig. B.35, is identified tentatively by Knobel with HIP 12093 (ν Cet), near 14.5,7.9, closer but fainter (d=79′.1, V=4.9) than our preferred counterpart.

U 785, near −10.6,14.7 in Fig. B.37, is identified by Knobel with HIP 13421, which at V=6.3 is considered by us too faint to be a probable counterpart. We leave U 785 unidentified.

U 882-884, near 11,−10 in Figs. B.41 and B.42, are identified by us with the three nearest stars. Knobel identifies U 884 with the fainter, almost equally distant HIP 43105 (V=4.5, d=128′.8), near 12.3,−13.0, and U 883 with our identification of U 884.

U 901, the faint star near −25.0,−2.0 in Fig. B.43, is identified by Knobel with HIP 46404, near −25.4,−0.3. We consider this star too far, and perhaps too bright, to be a probable counterpart, and leave U 901 unidentified.

U 903-905, near −16.4,−5.0, −15.0,−2.0, and −14.2,−0.7, respectively in Fig. B.43, correspond in description to P 906-908 in *Ptolemaios*, but their positions are shifted, such that U 903 has the same Hipparcos counterpart as P 907 and U 904 as P 908. U 905 has the Hipparcos counterpart which is our tentative identification for P 920, the last star of Argo in *Ptolemaios*.

U 952 corresponds to P 955 and is the globular cluster ω Cen.

U 961, corresponding to P 964, has no position from Ulugh Beg, as he could not see it.

U 979, is tentatively identified by Knobel with Lacaille 5709; HIP 67652 is the nearest Hipparcos star with V <7.5 (at 3′.3). At V = 7.2 this is not a possible counterpart for U 979. We leave U 979 unidentified.

Appendix B: Figures

To illustrate and clarify our identifications we provide a Figure for each constellation. To facilitate comparison each figure shows the graph for Ptolemaios on the left and for Ulugh Beg on the right. In these figures the stars listed with the constellation in *Ptolemaios* / *UlughBeg* are shown red, and other stars from the same catalogue in purple. Positions in the edition of the star catalogue of Ptolemaios by Manitius (1913), when very different from those in the Toomer (1998) edition, are indicated in brown, connected by a dashed line to the position in the edition by Toomer (1998).

To minimize deformation of the constellations, we determine the center of the constellation λ_c, β_c from the extremes in λ and β, compute the rotation matrix which moves this center to $(x, y, z) = (1, 0, 0)$, and then apply this rotation to each of the stellar positions λ_i, β_i. (For exact details see Verbunt & van Gent 2010a.) The resulting y, z values correspond roughly to differences in longitude and latitude, exact at the center λ_c, β_c and increasingly deformed away from the center. We plot the rotated positions of the stars in *Ptolemaios* / *UlughBeg* as $d\lambda \equiv y$ and $d\beta \equiv z$ with filled circles. The same rotation matrix is applied to all stars down to a magnitude limit V_m (usually $V_m = 6.0$) from the *Hipparcos Catalogue* and those in the field of view are plotted as open circles. The symbol sizes are determined from the magnitudes as indicated in the legenda. The used values for λ_c, β_c and V_m are indicated with each Figure.

We show enlarged detail in Figures 2, 1, 3 and B.24; for easy comparison with the Figures showing the whole constellation, these detail Figures use the same rotation center (and thus rotation matrix).
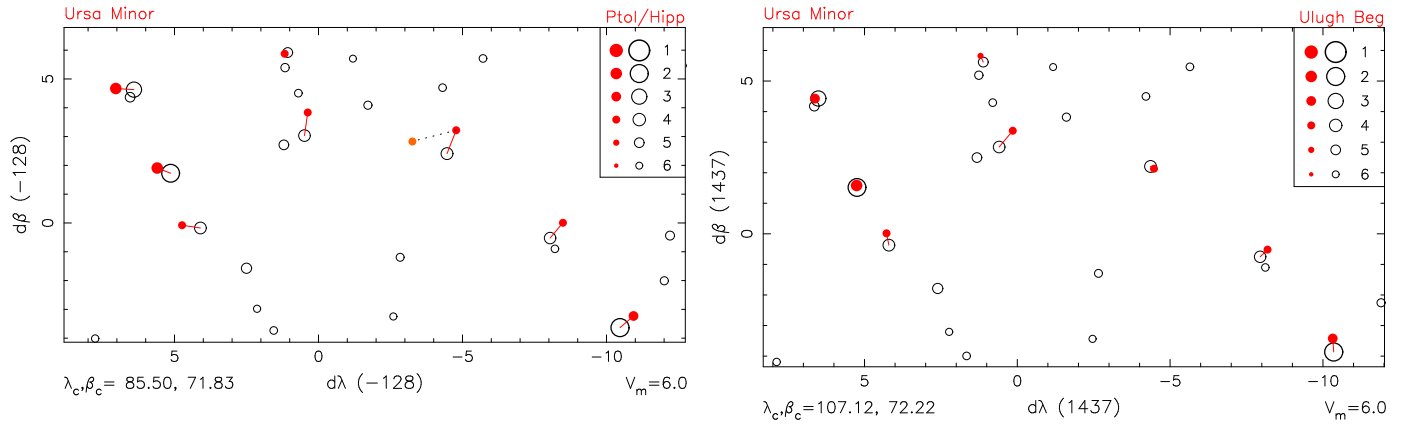
Figure B.1. Ursa Minor
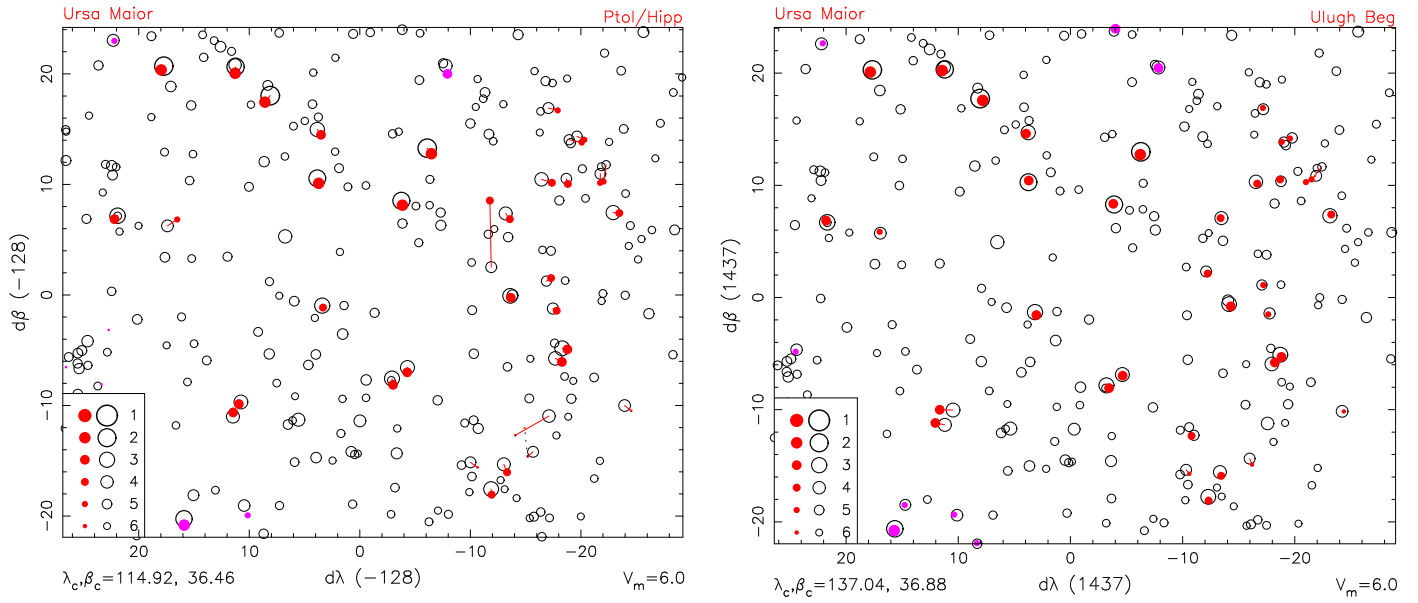
Figure B.2. Ursa Maior
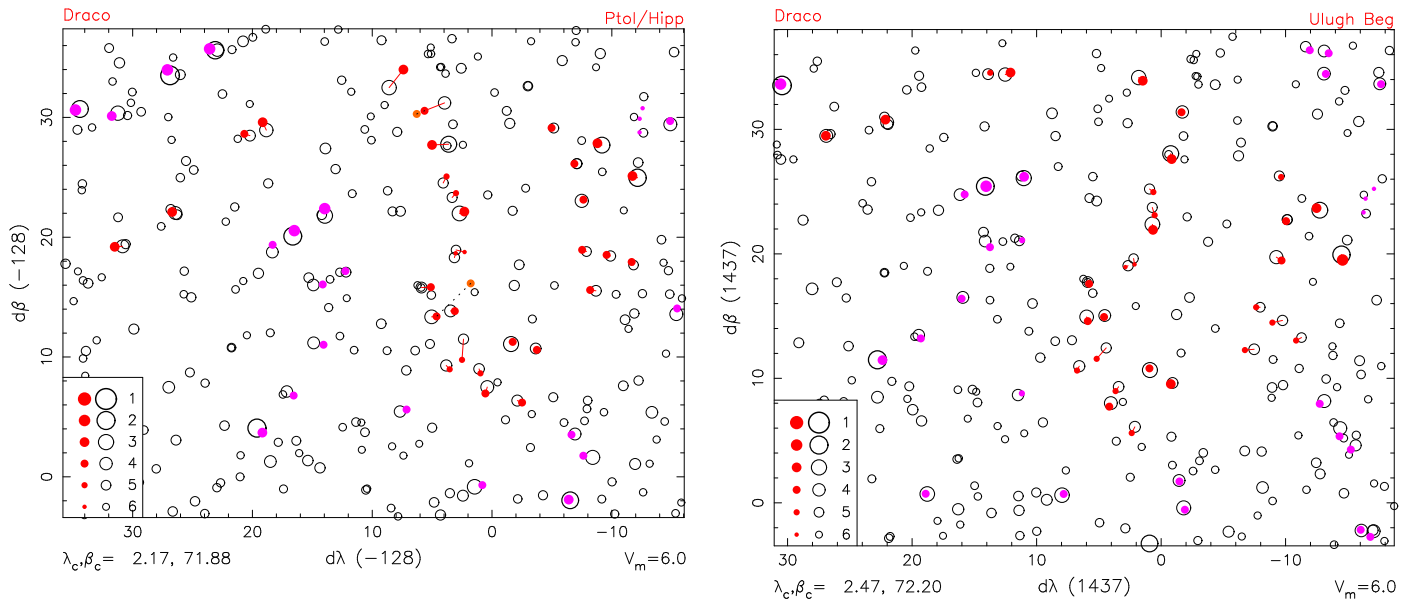
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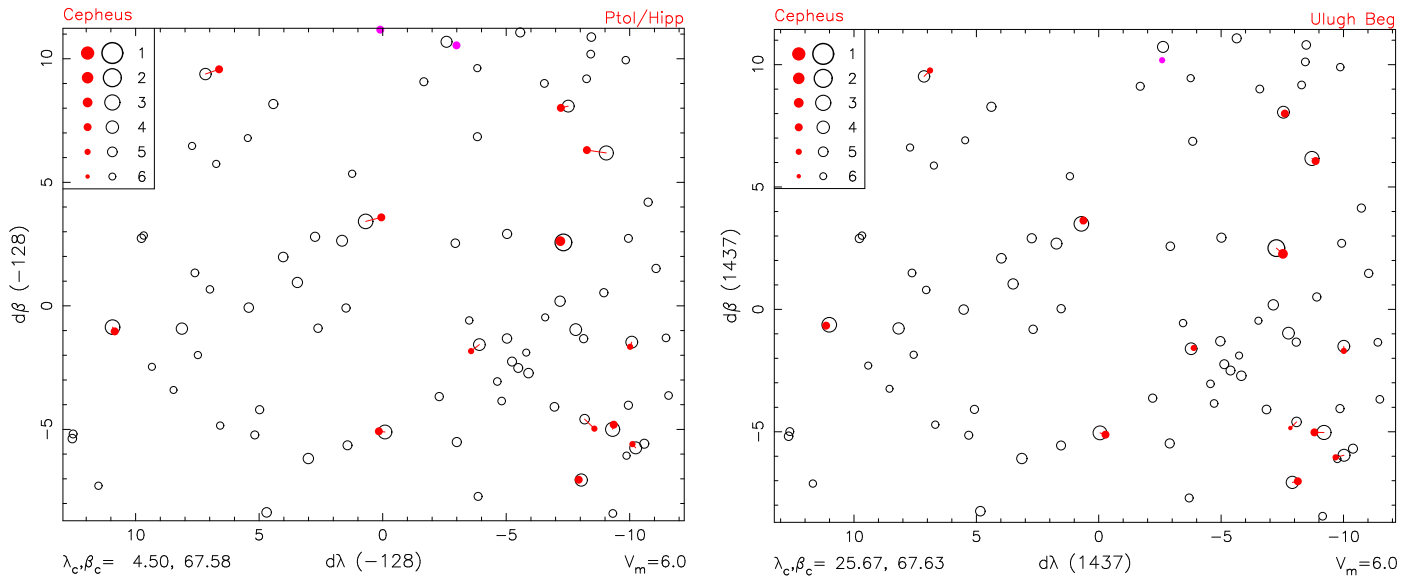
Figure B.4. Cepheus
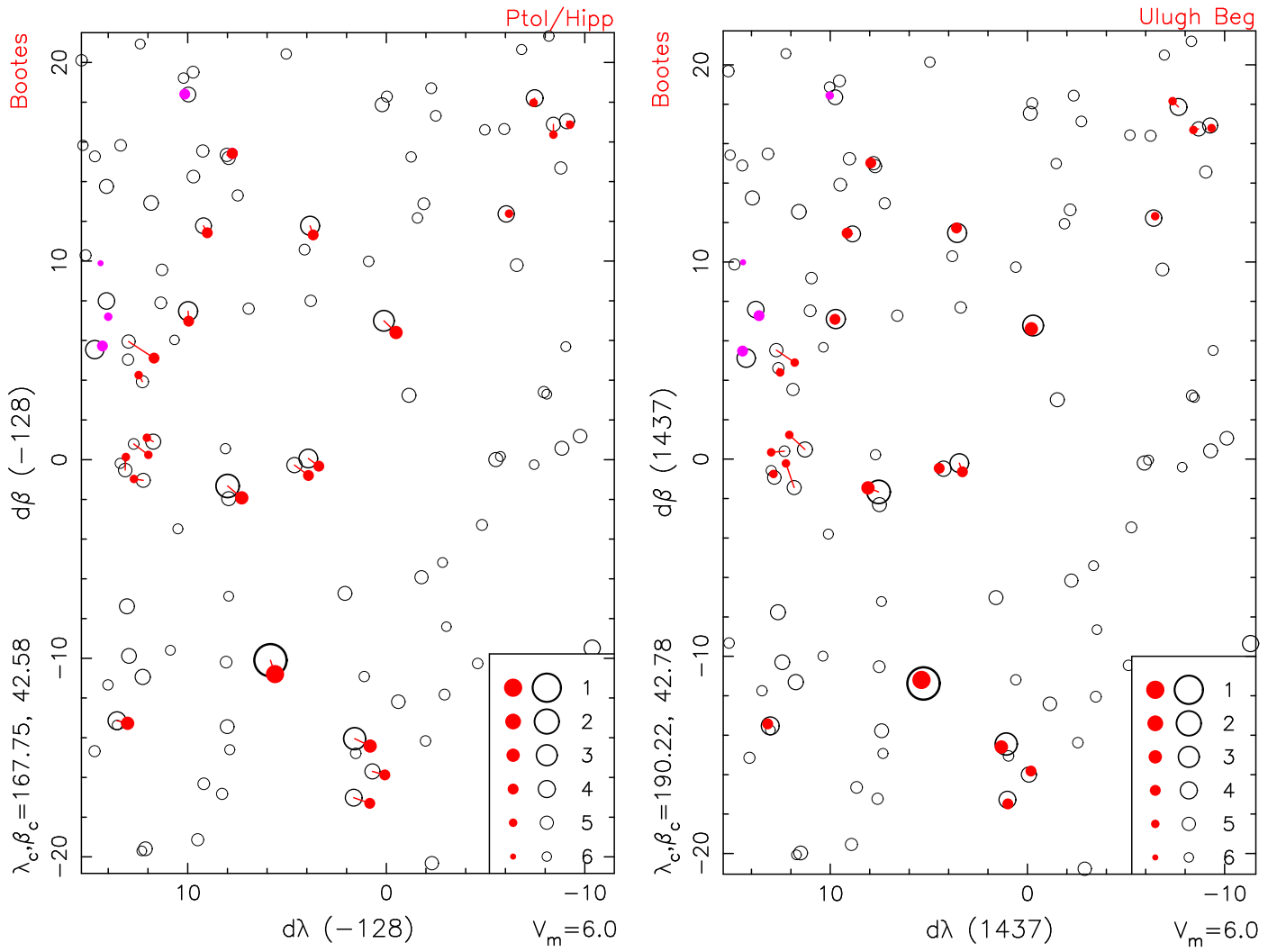
Figure B.5. Bootes
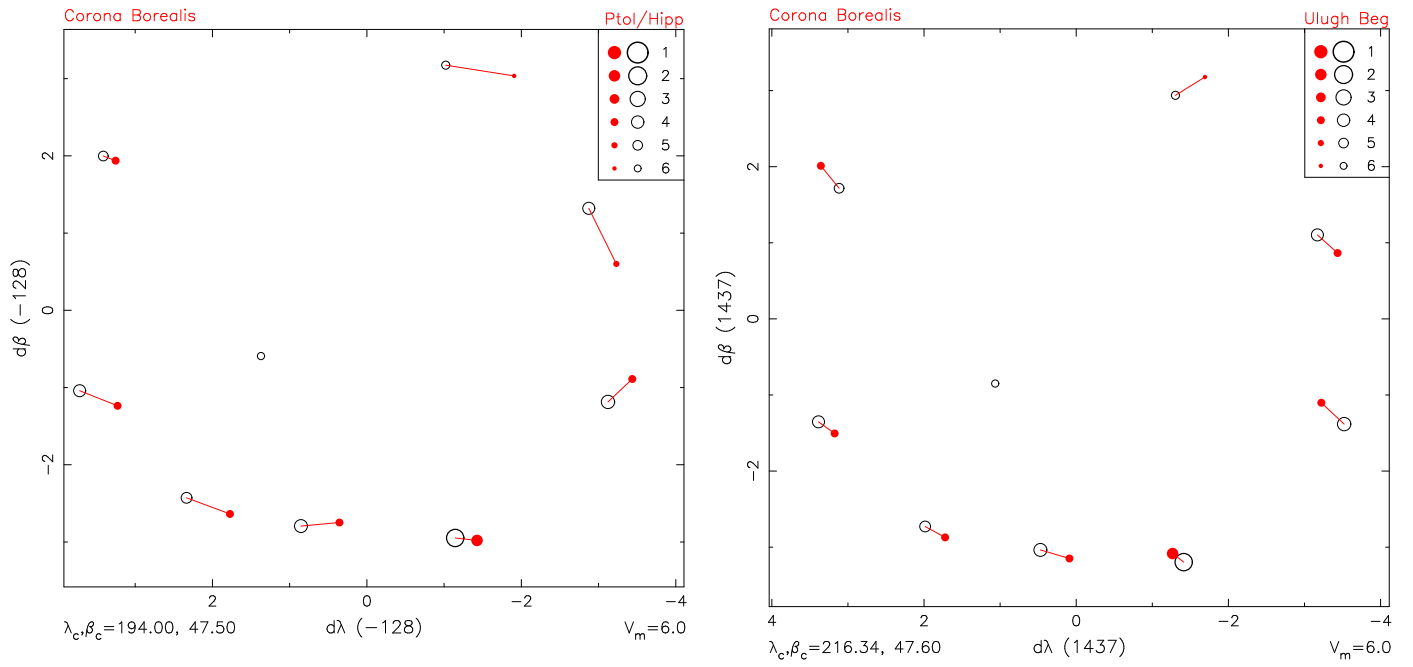
Figure B.6. Corona Borealis
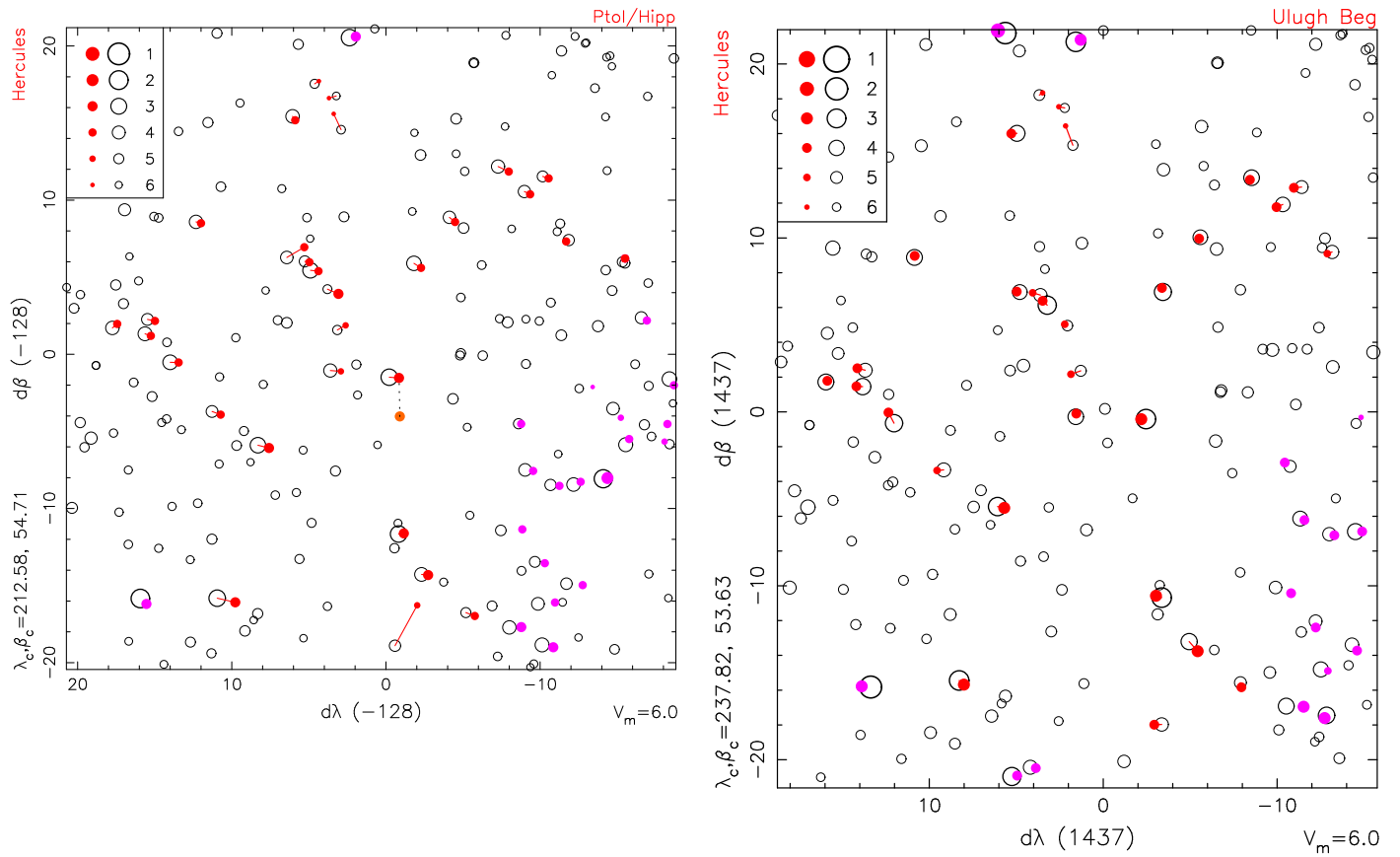
Figure B.7. Hercules
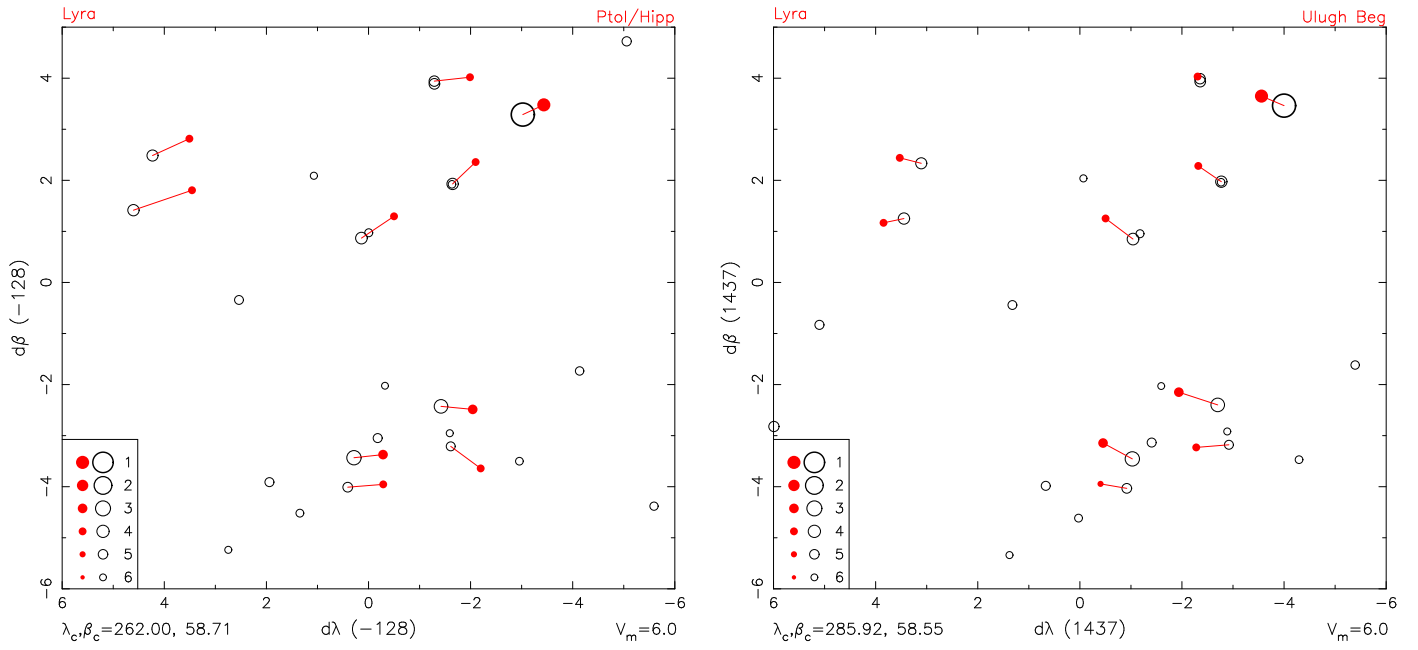
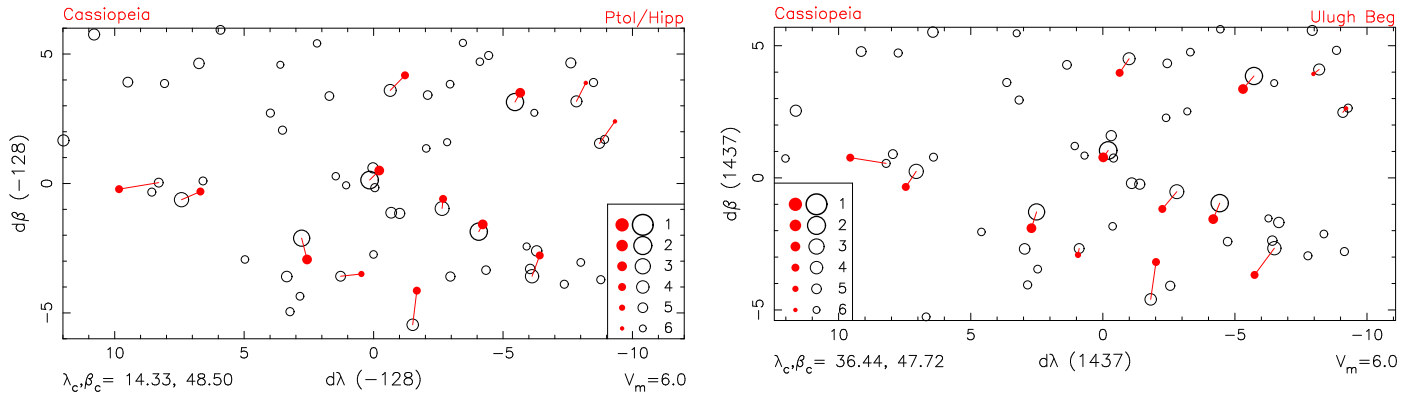**Figure B.8.** Lyra
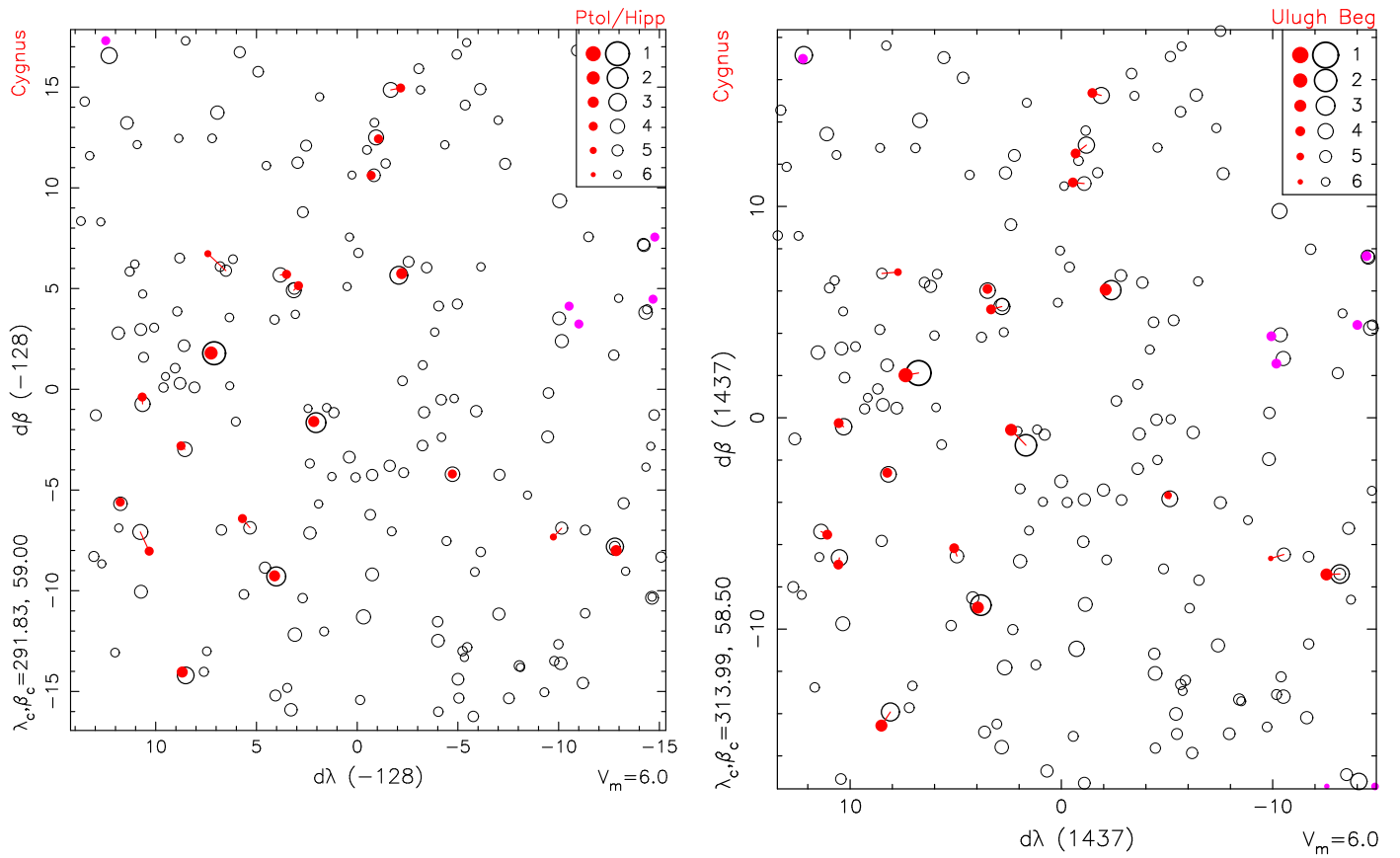
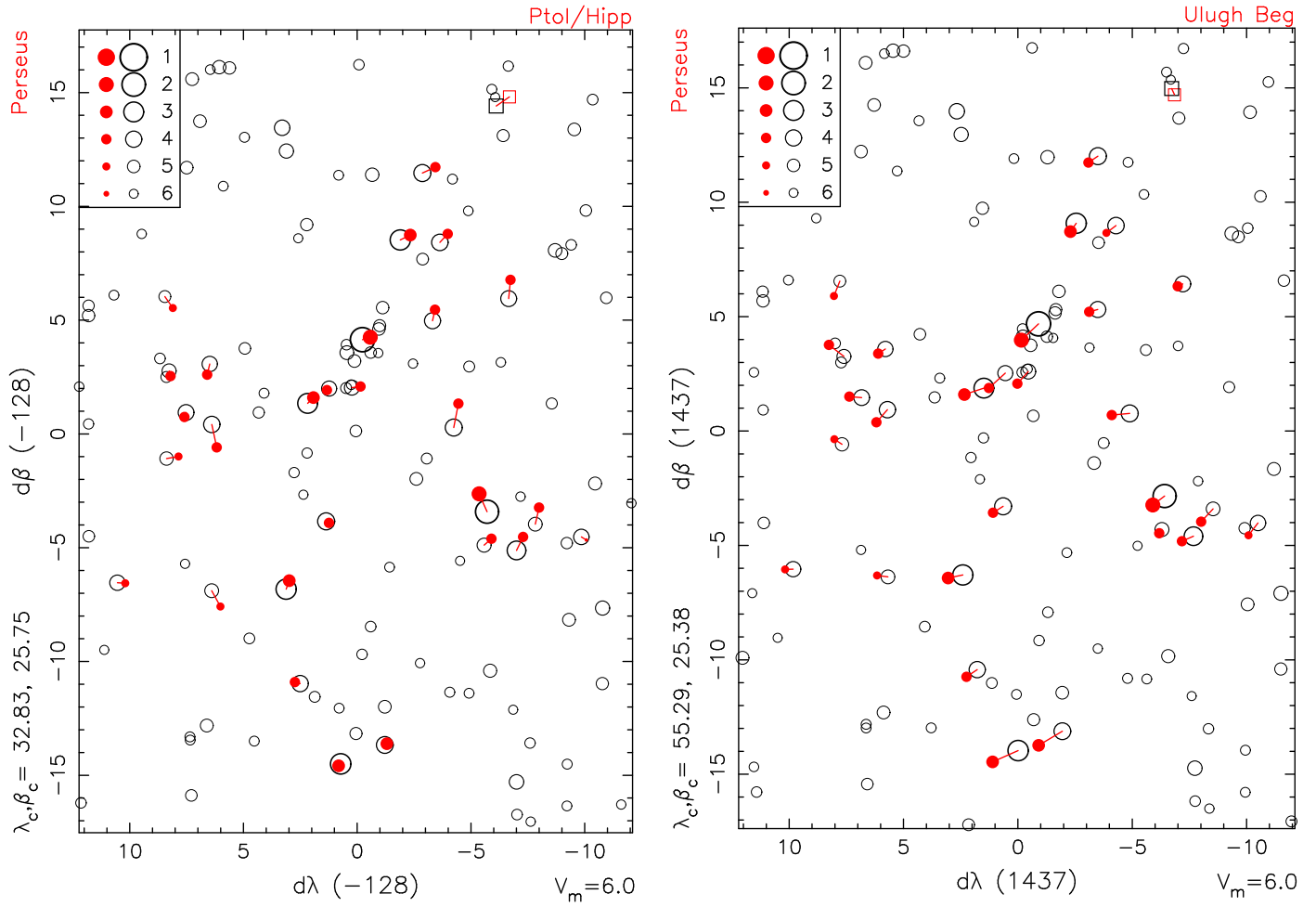**Figure B.9.** Cygnus

Figure B.10. Cassiopeia

Figure B.11. Perseus. The open cluster h Per is indicated with □ near −6,14
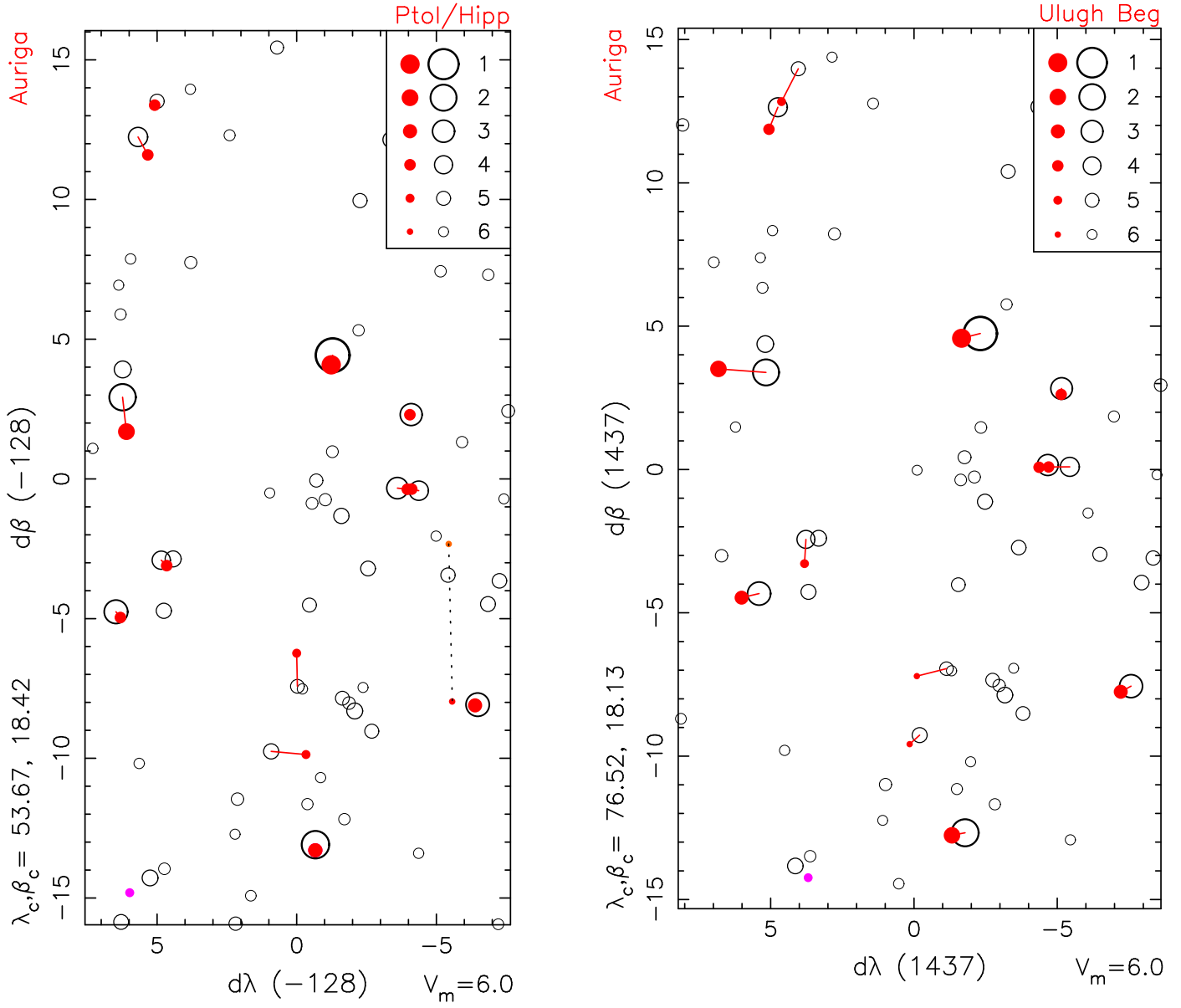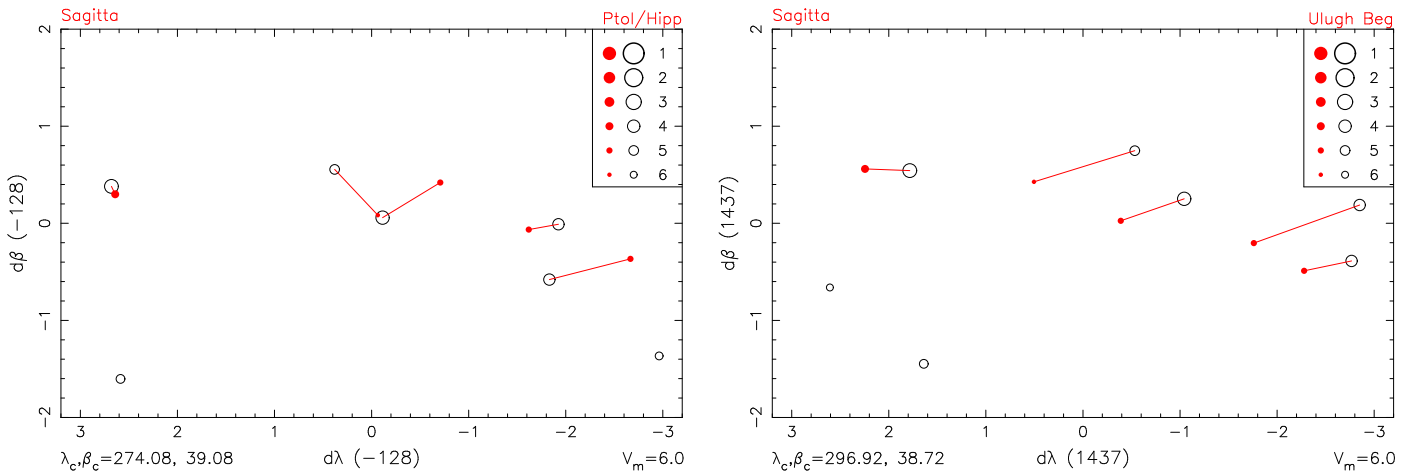
Figure B.12. Auriga

Figure B.13. Sagitta
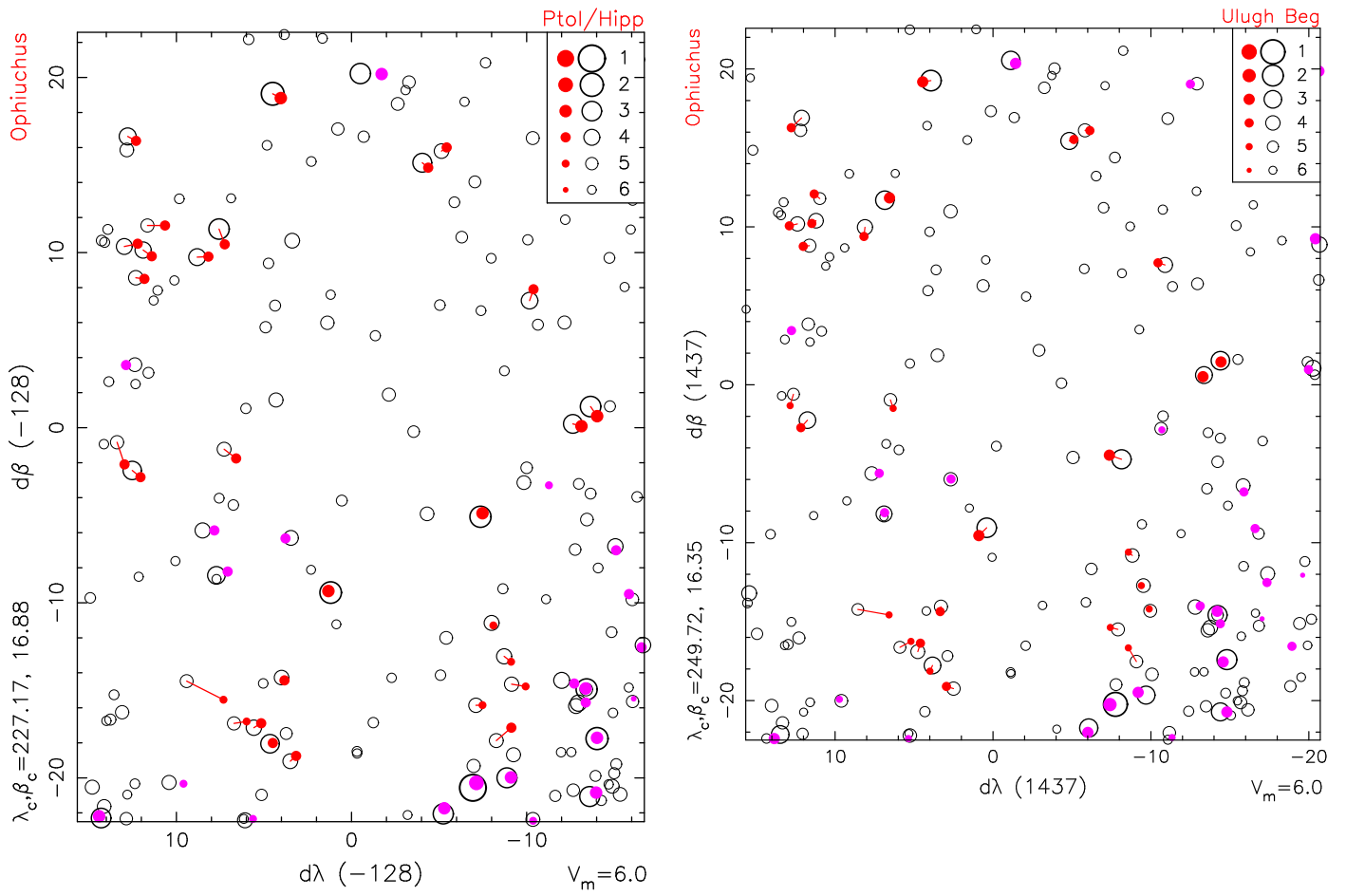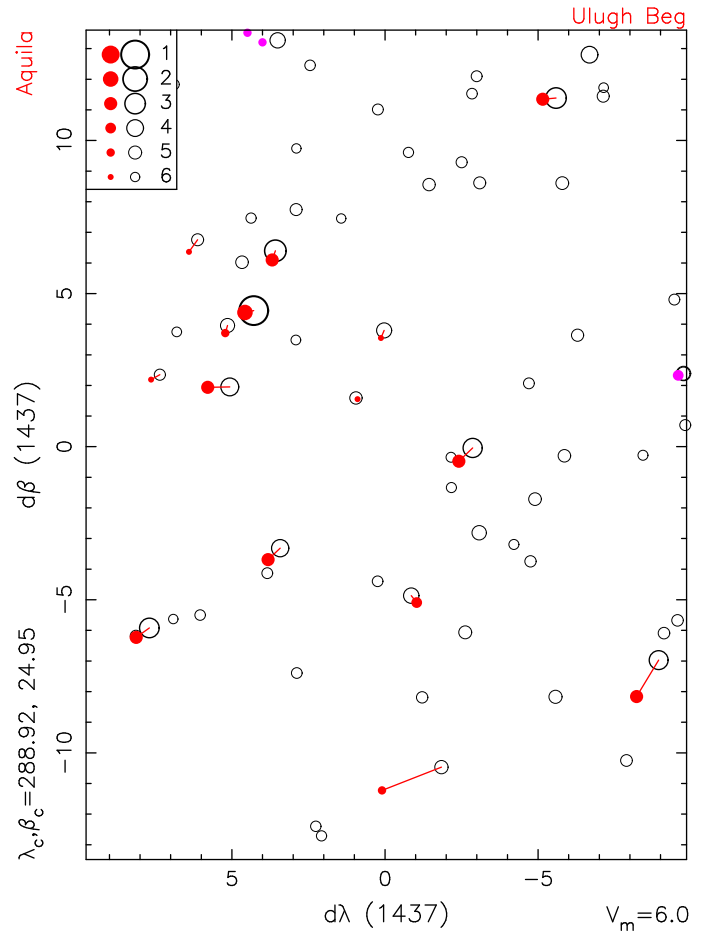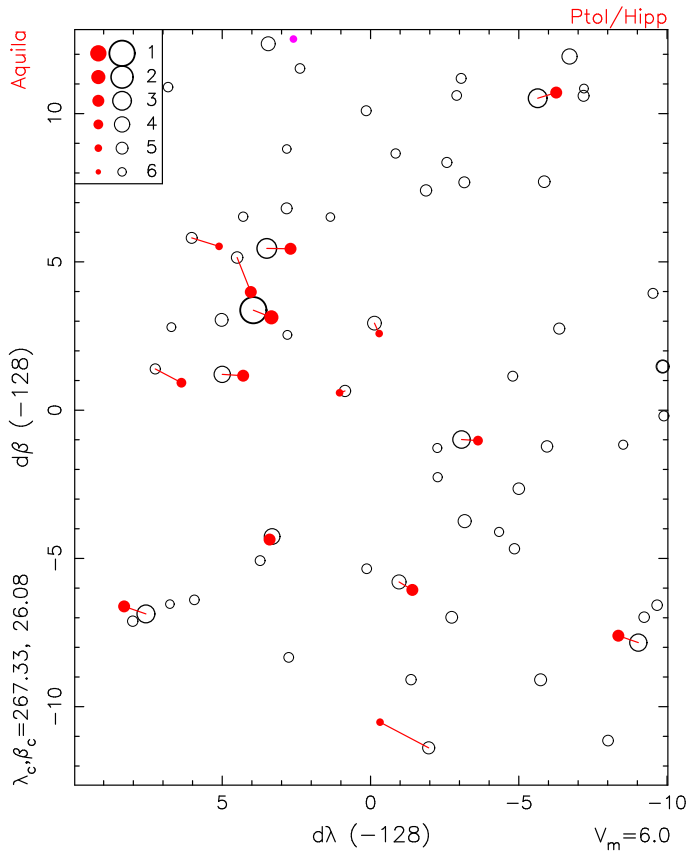
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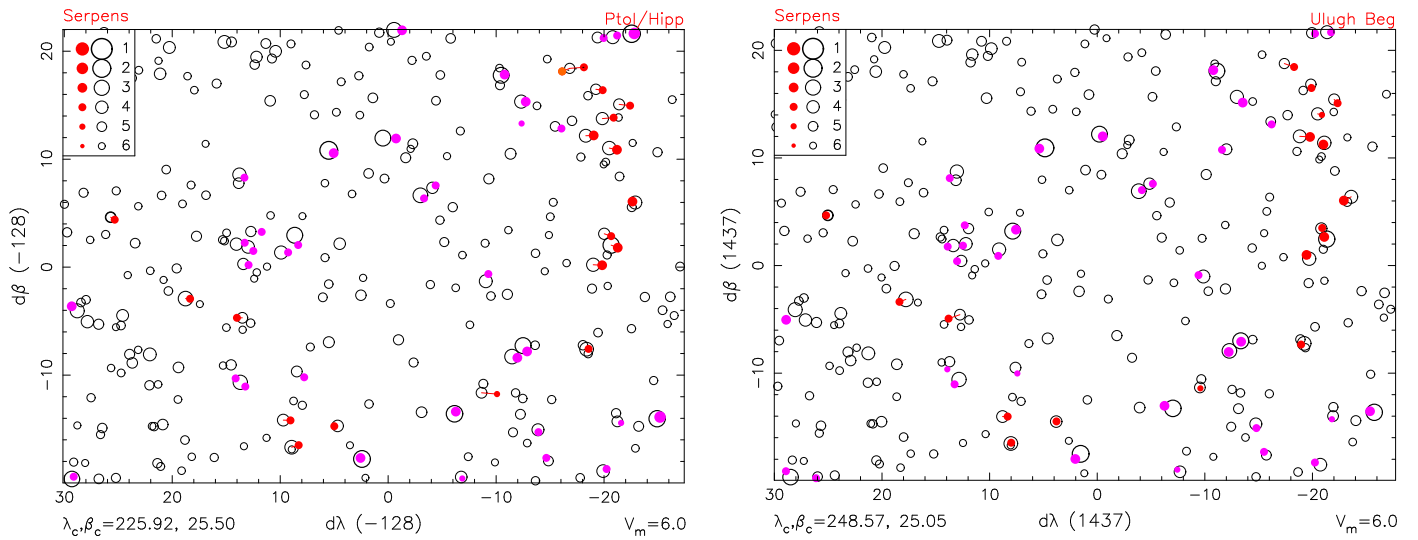
Figure B.15. Serpens

Figure B.16. Aquila
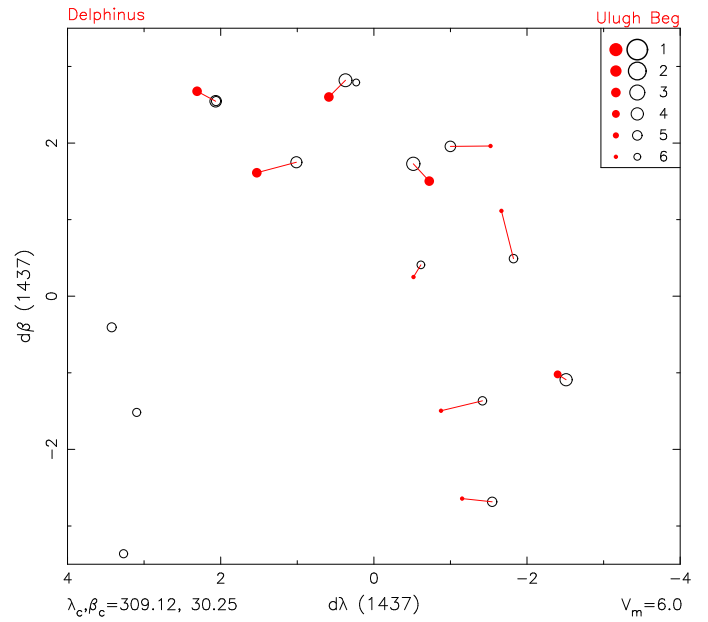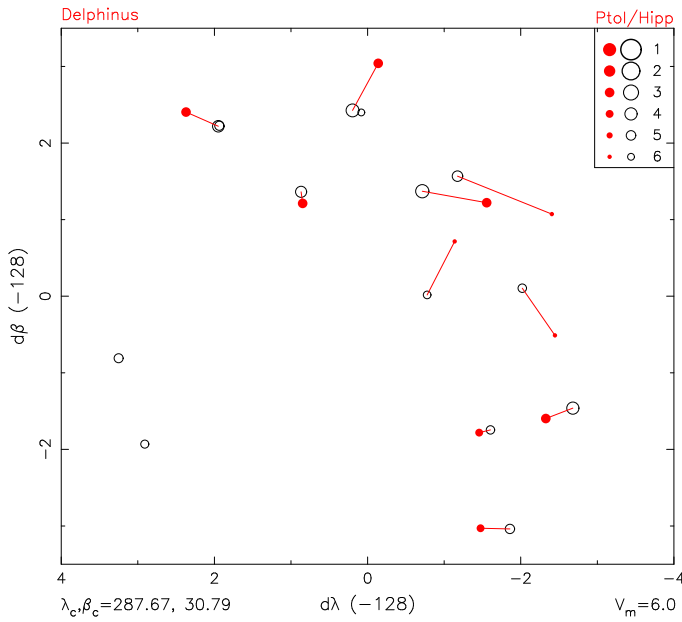
Figure B.17. Delphinus

20
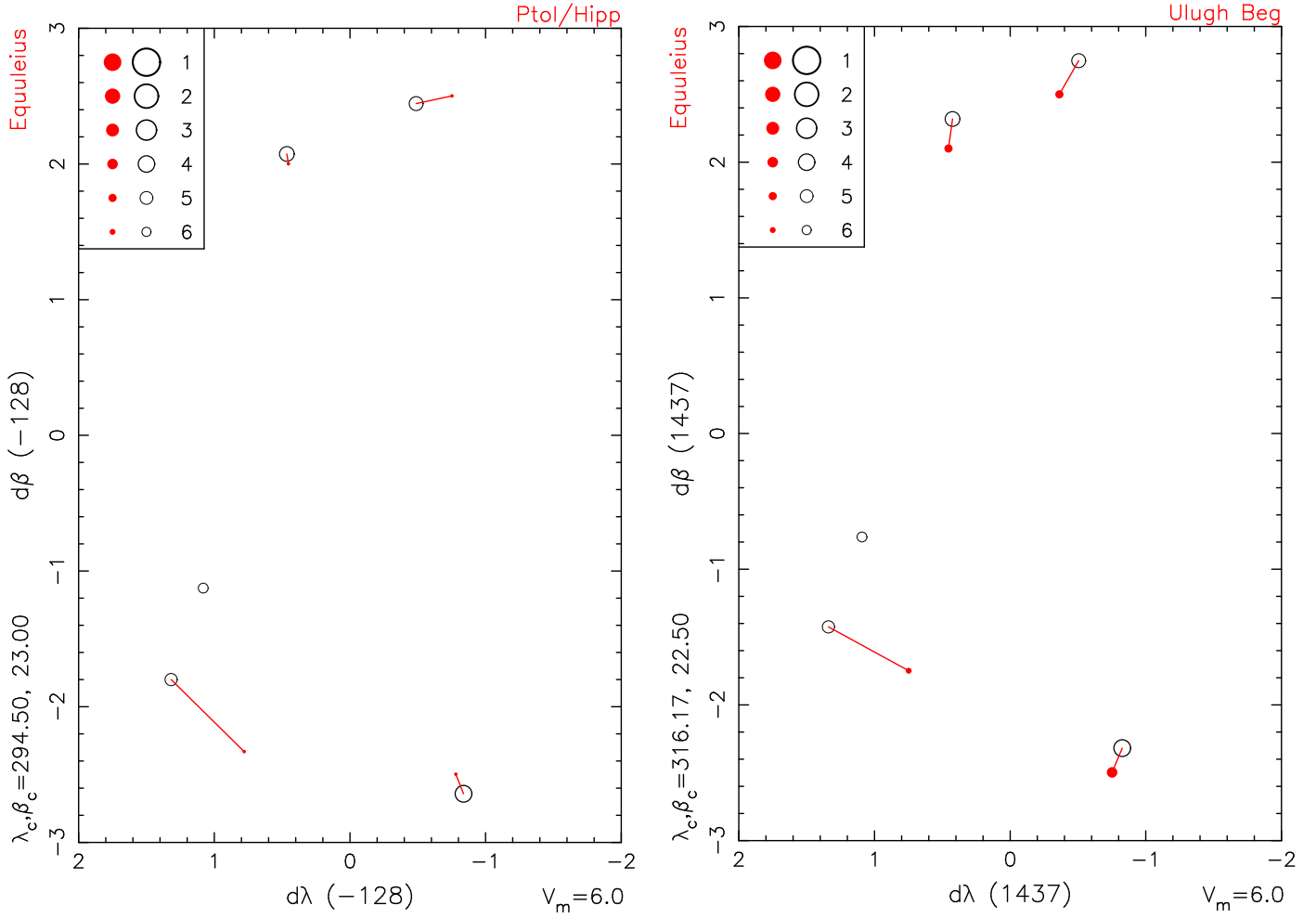
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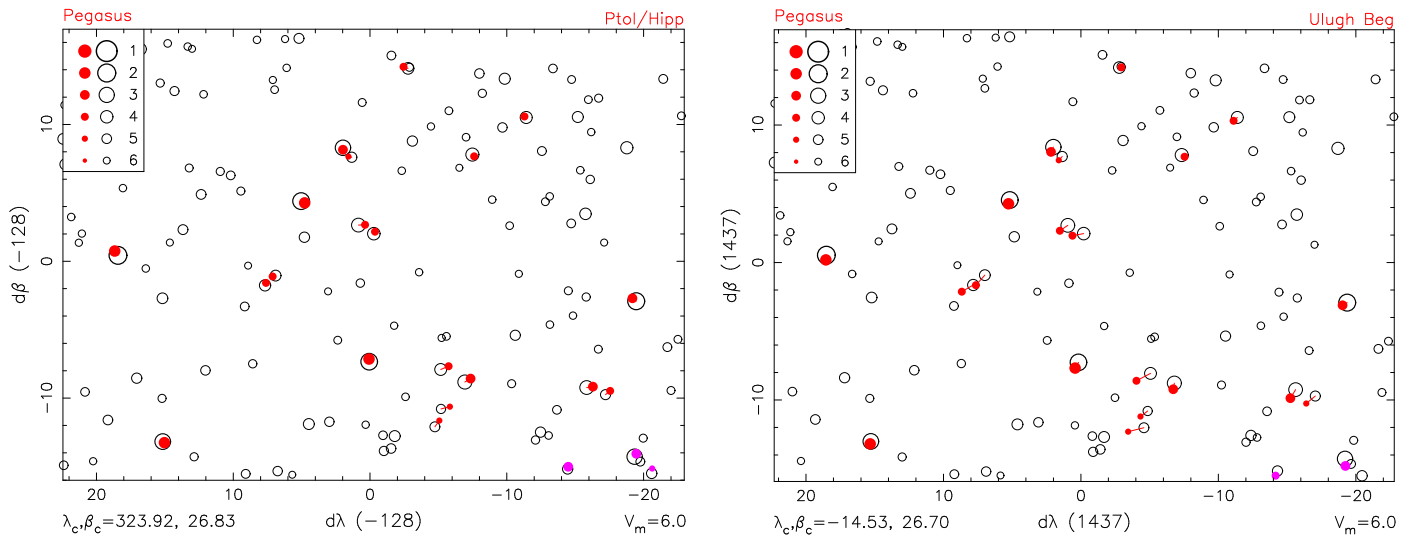
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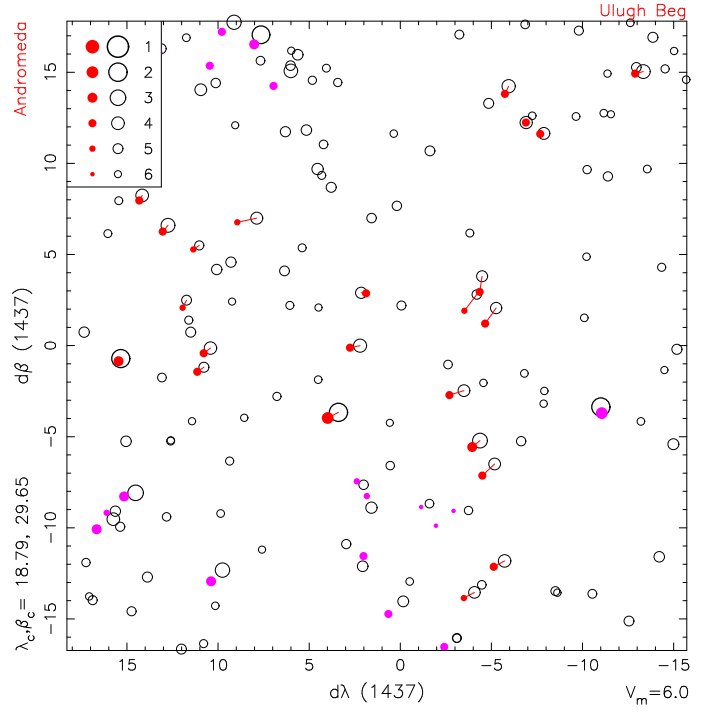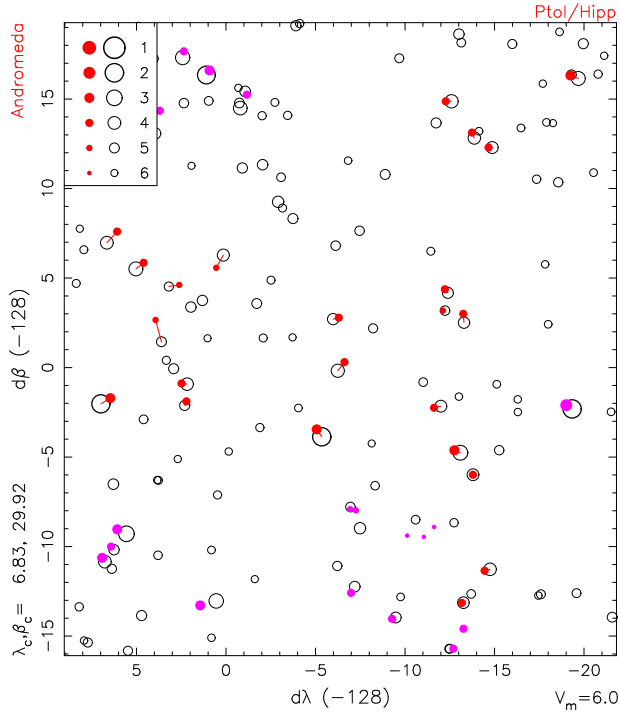
Figure B.20. Andromeda
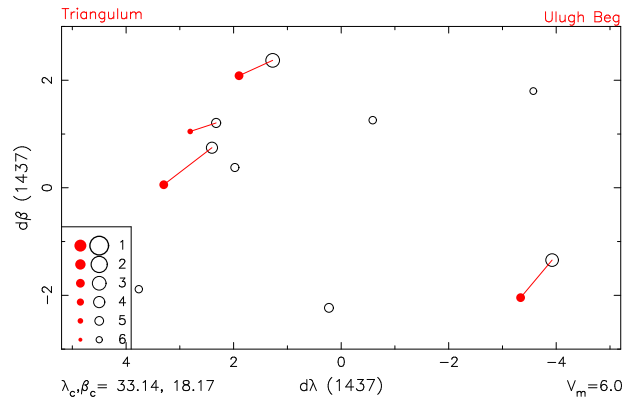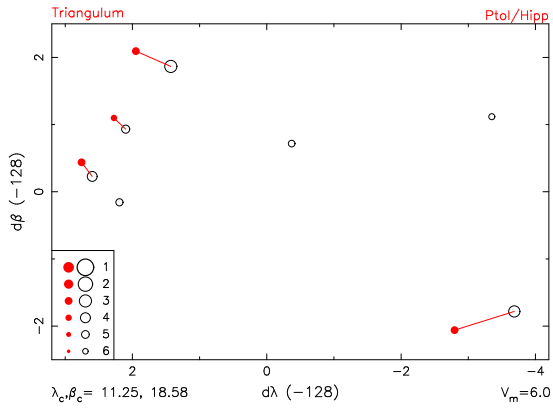
Figure B.21. Triangulum
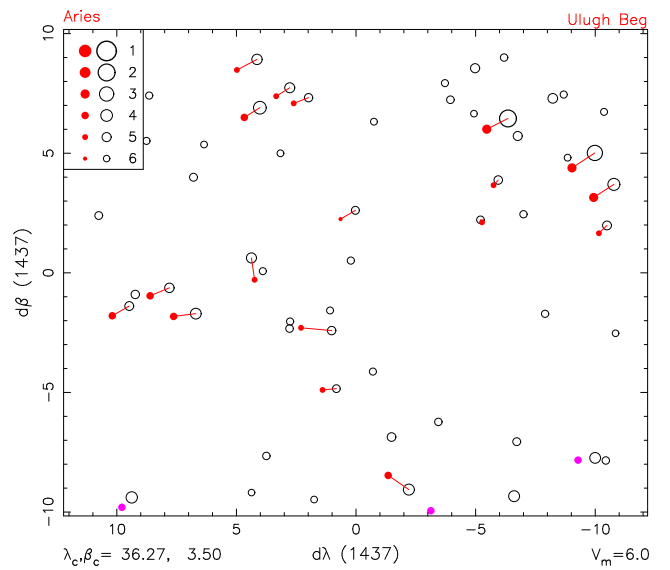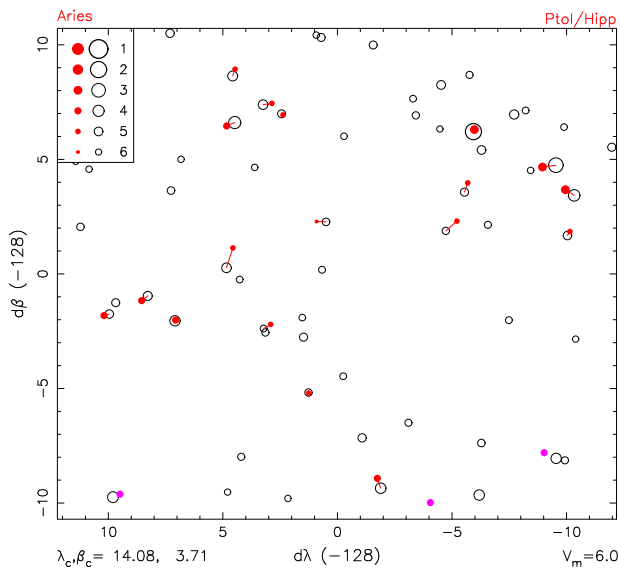
Figure B.22. Aries
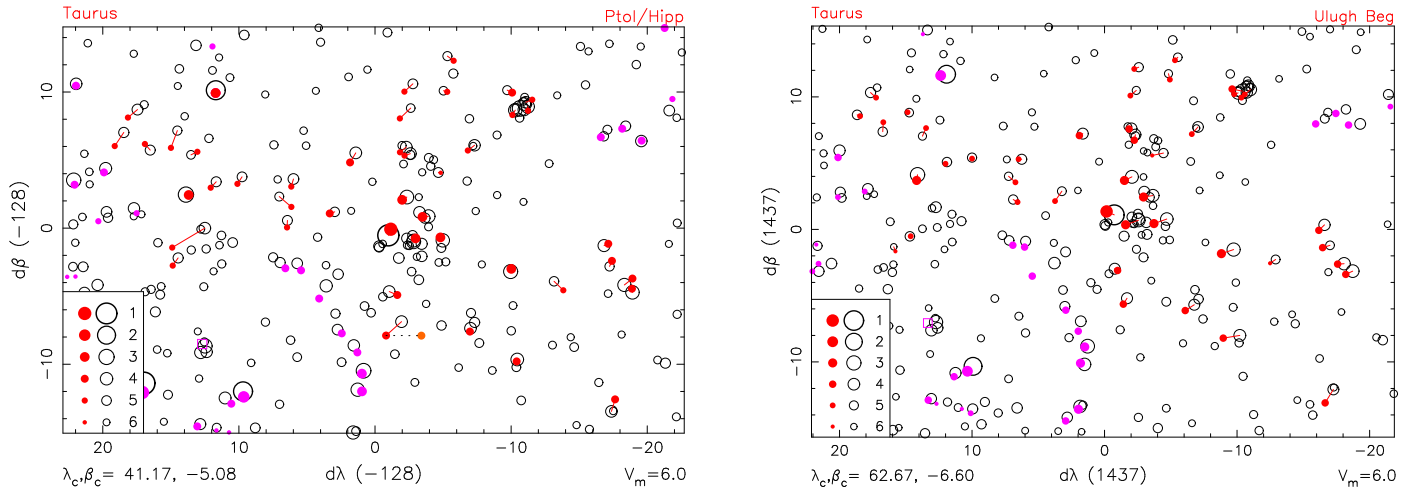
Figure B.23. Taurus
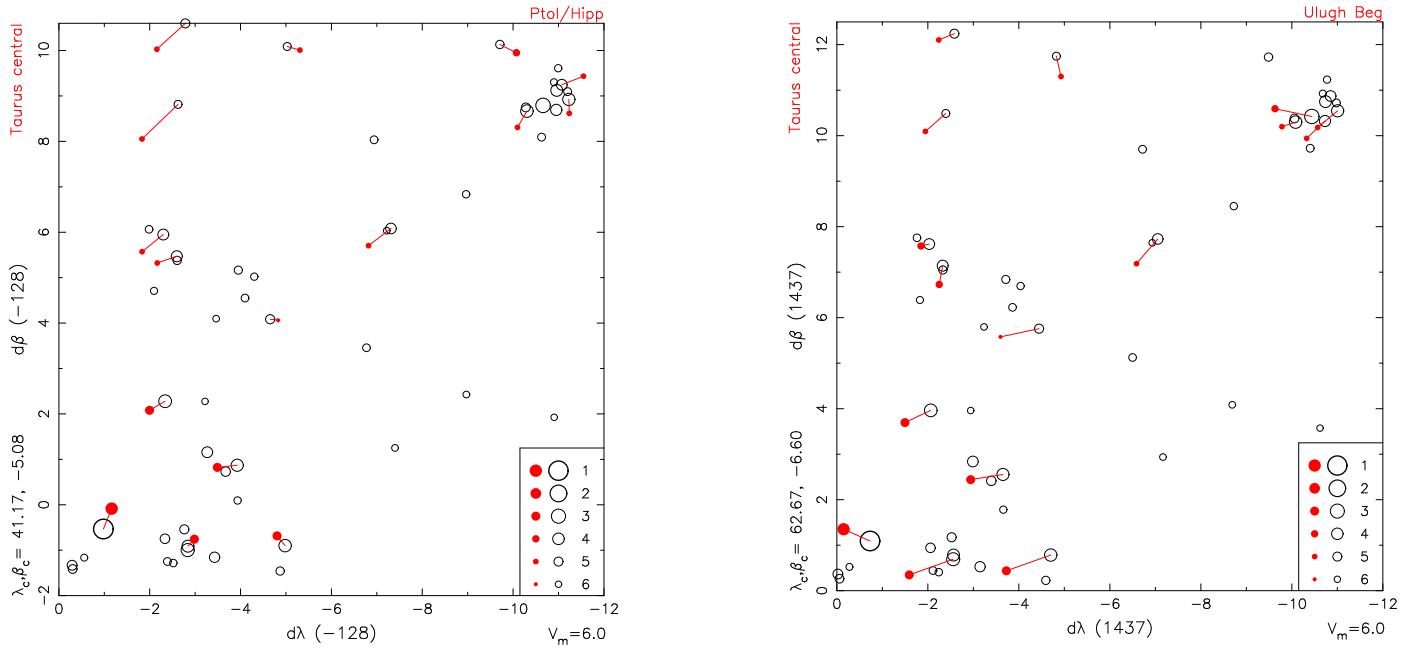
Figure B.24. Central area of Taurus
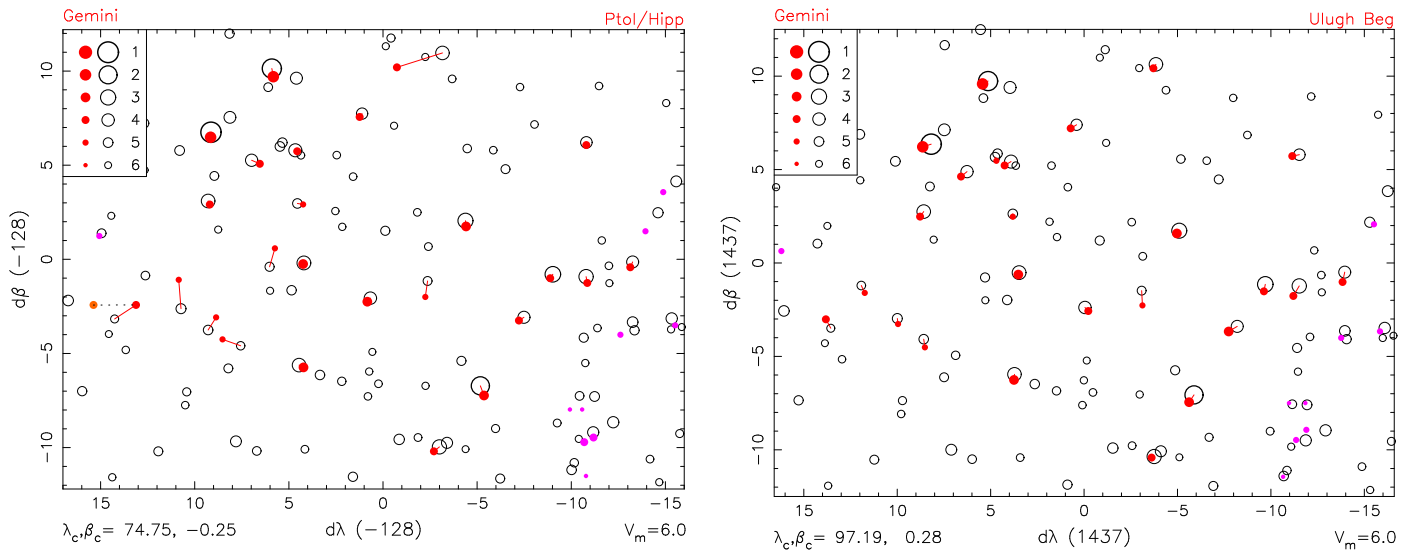
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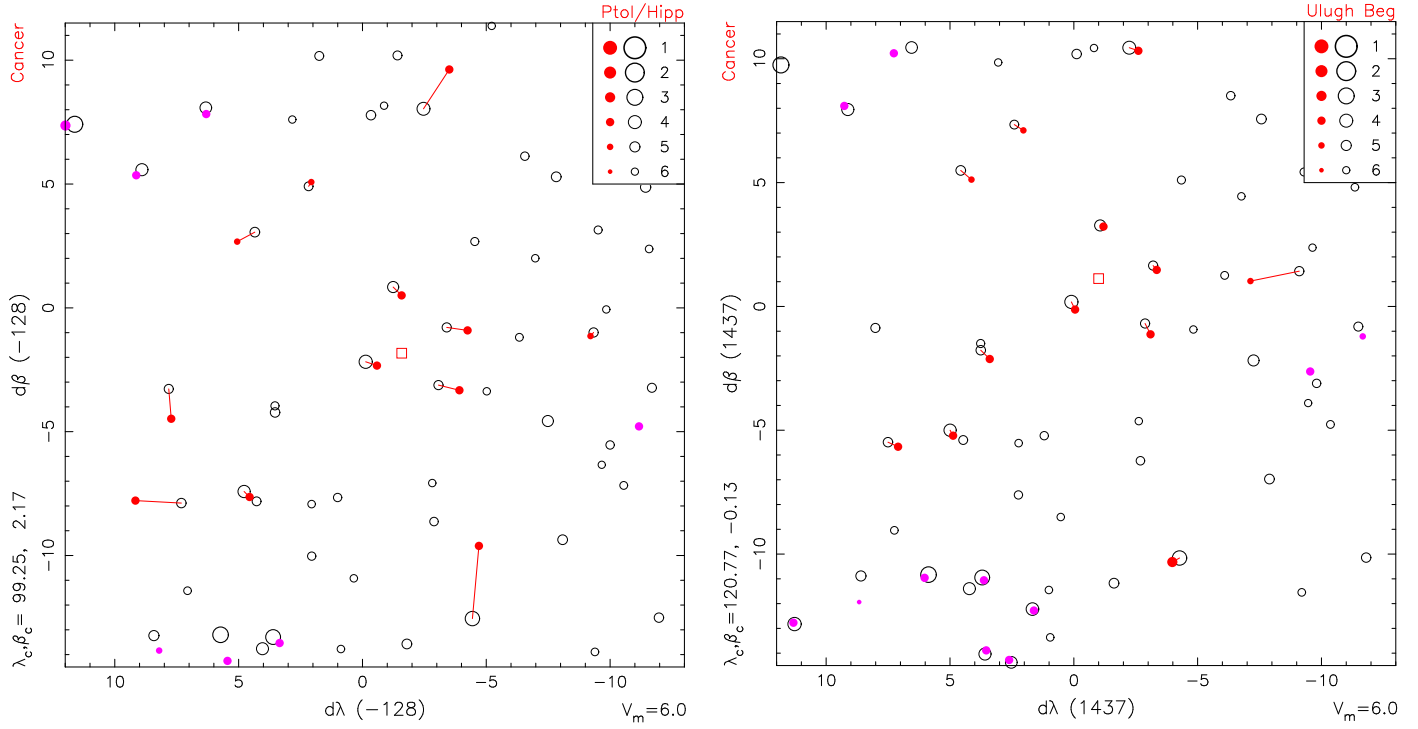
Figure B.26. Cancer
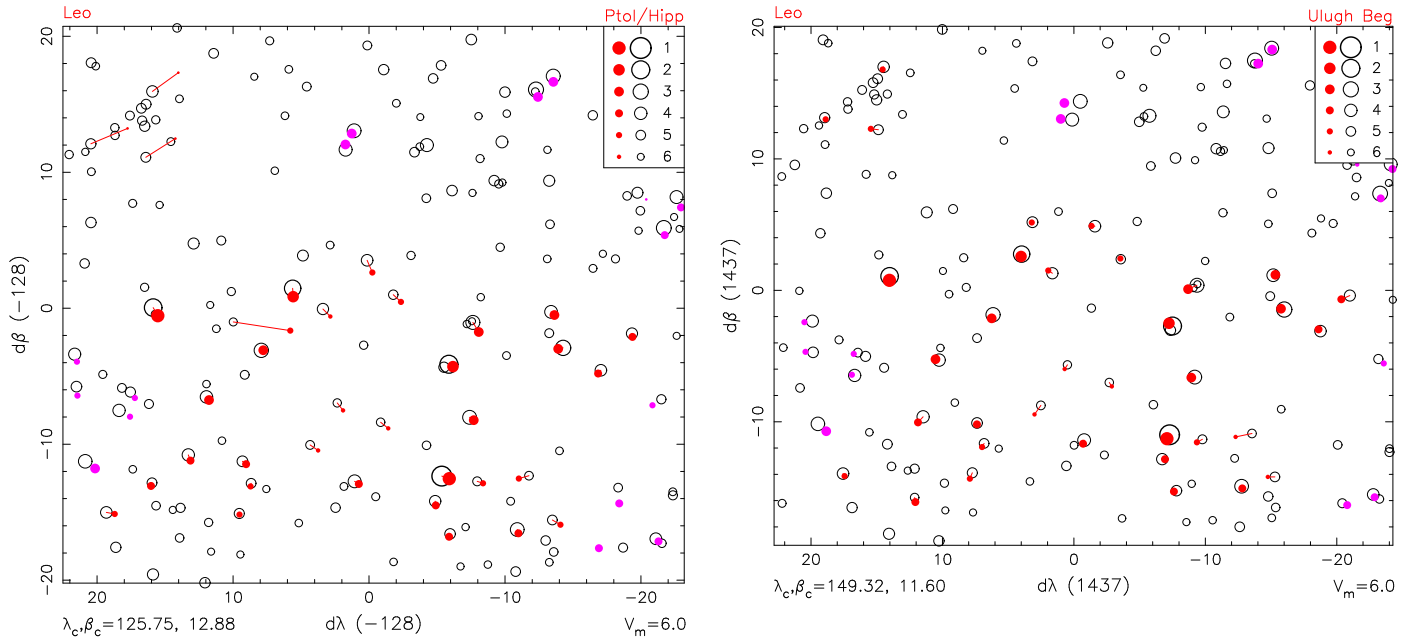
Figure B.27. Leo
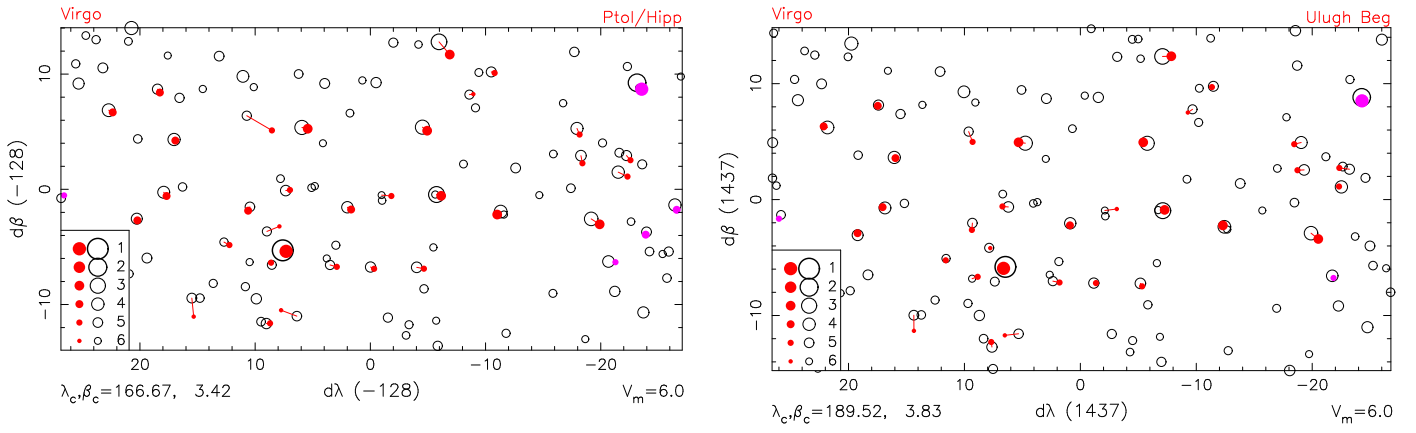
Figure B.28. Virgo
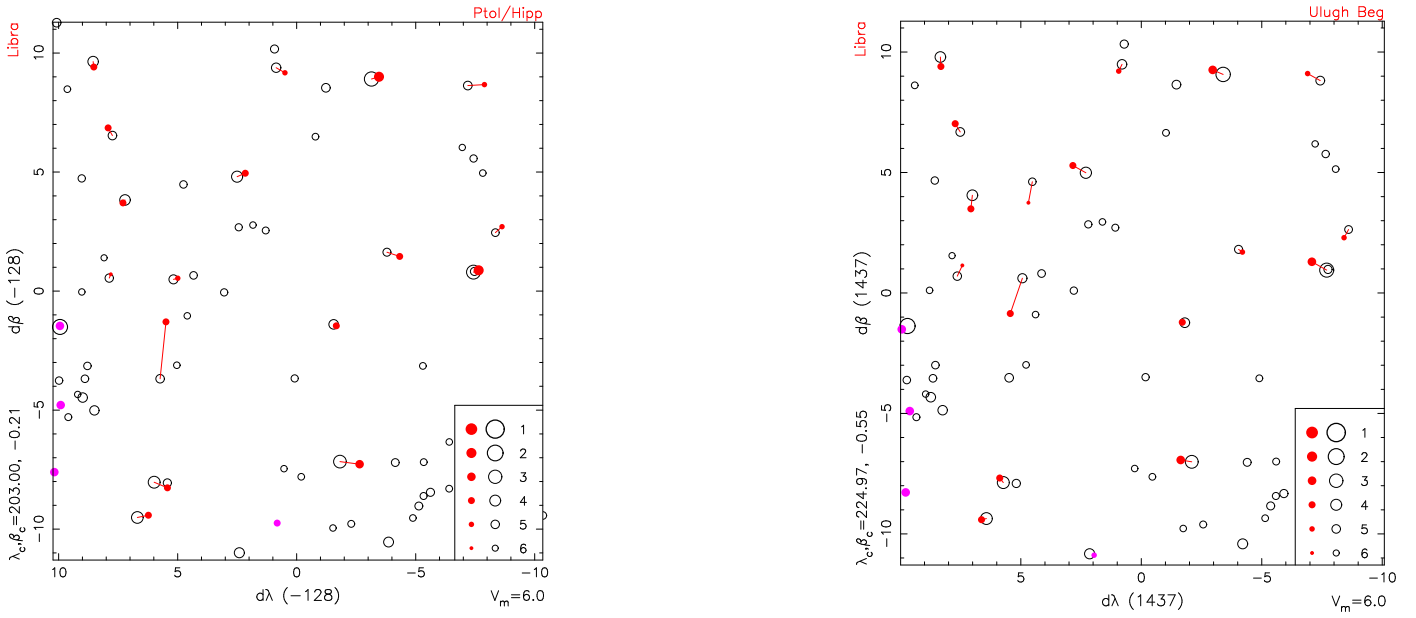
Figure B.29. Libra
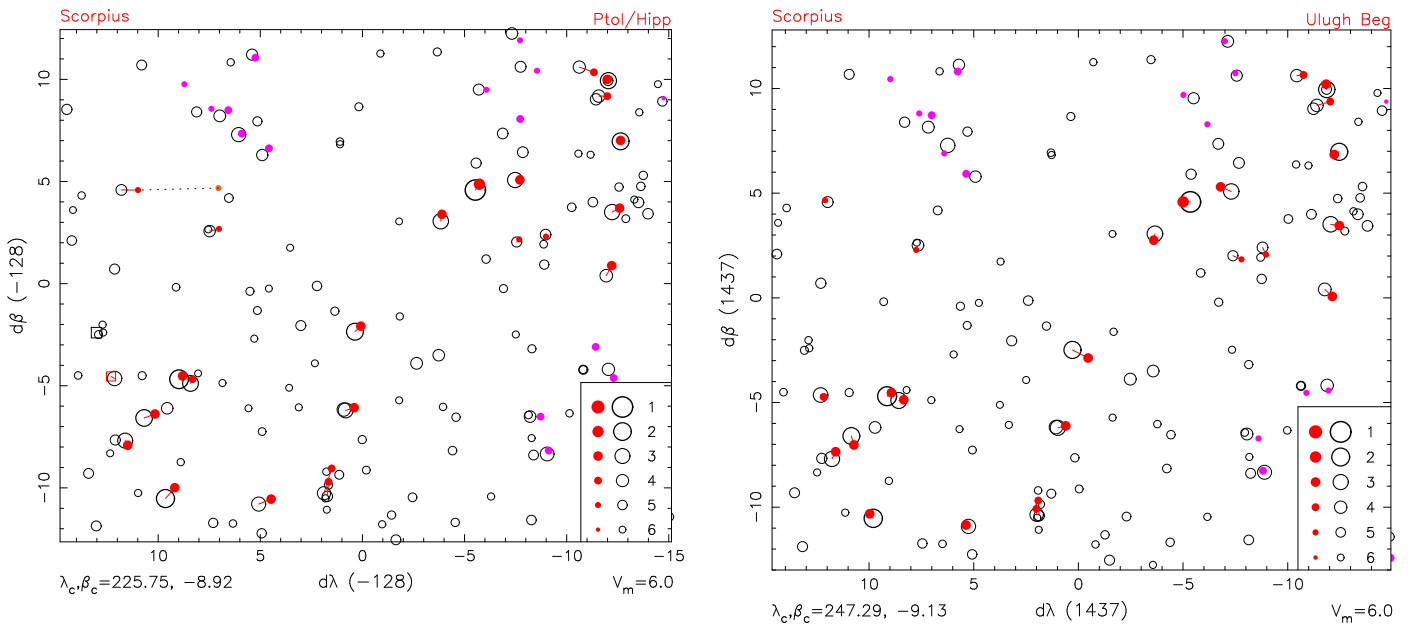
Figure B.30. Scorpius. In the left image, the □ near 13.0,−2.4 indicates M 7
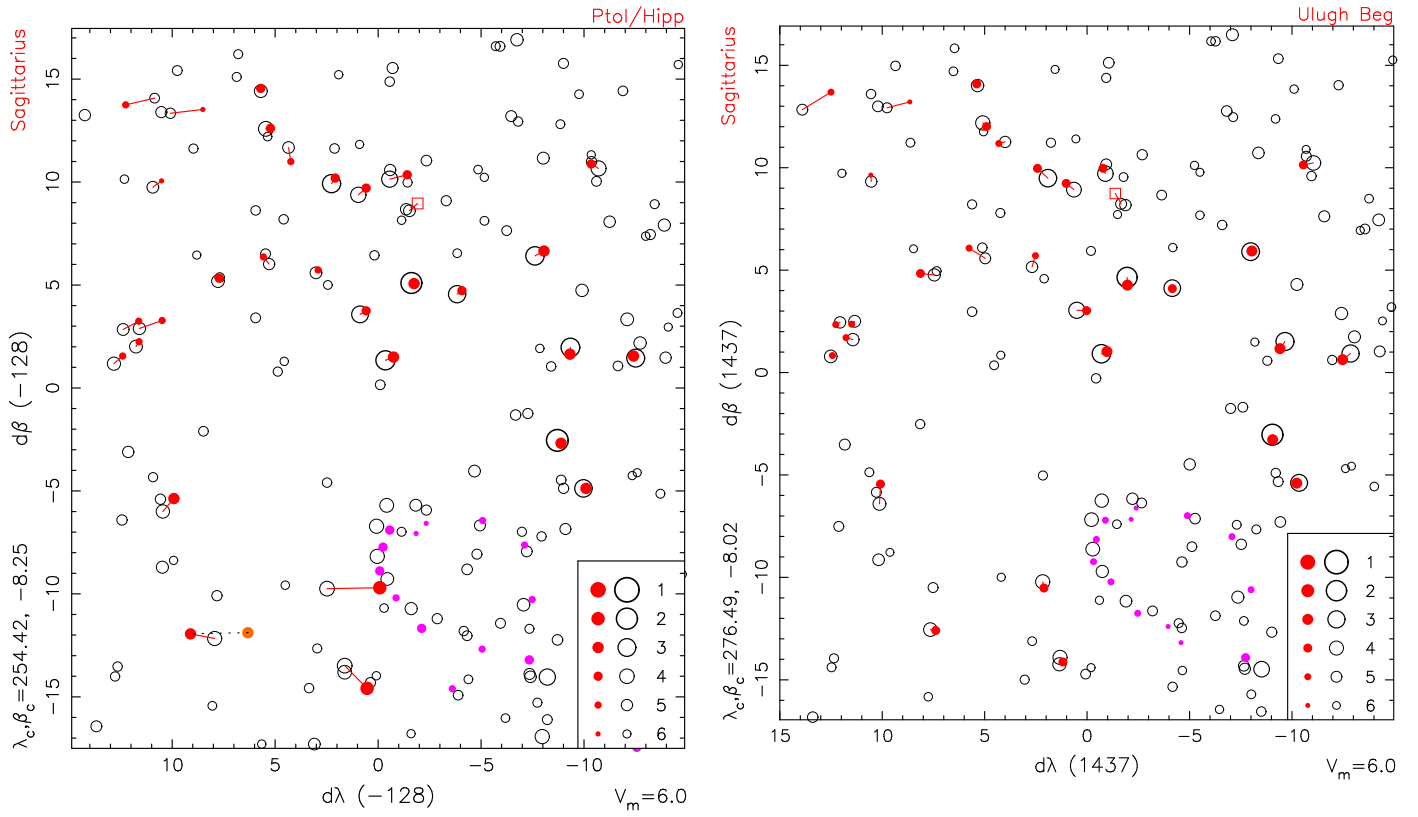
Figure B.31. Sagittarius
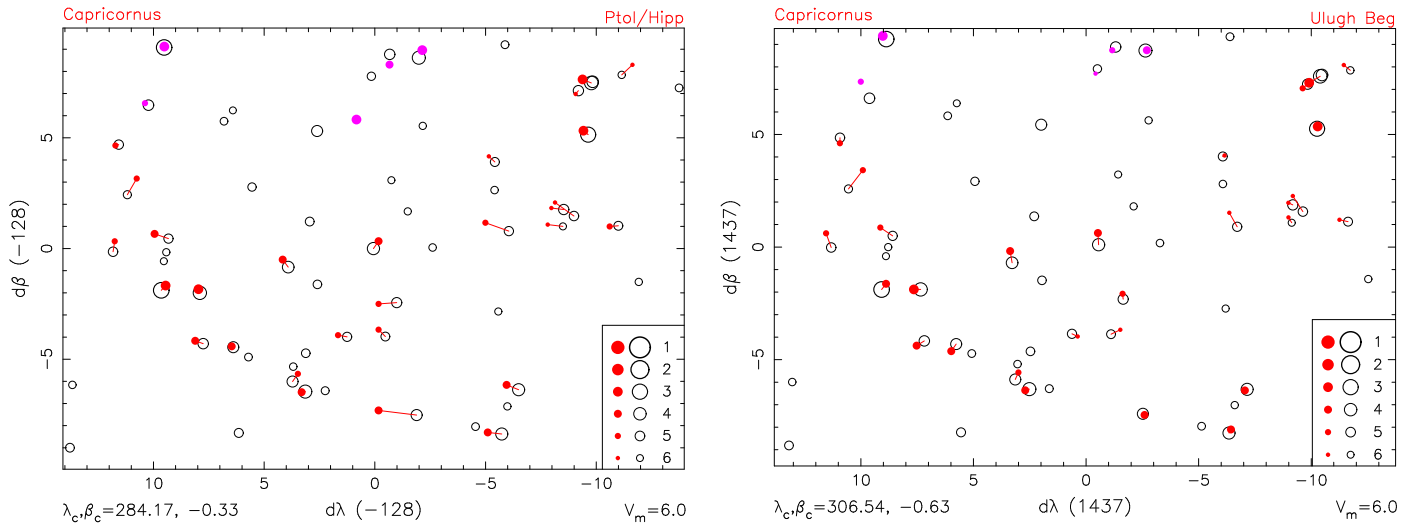
Figure B.32. Capricornus
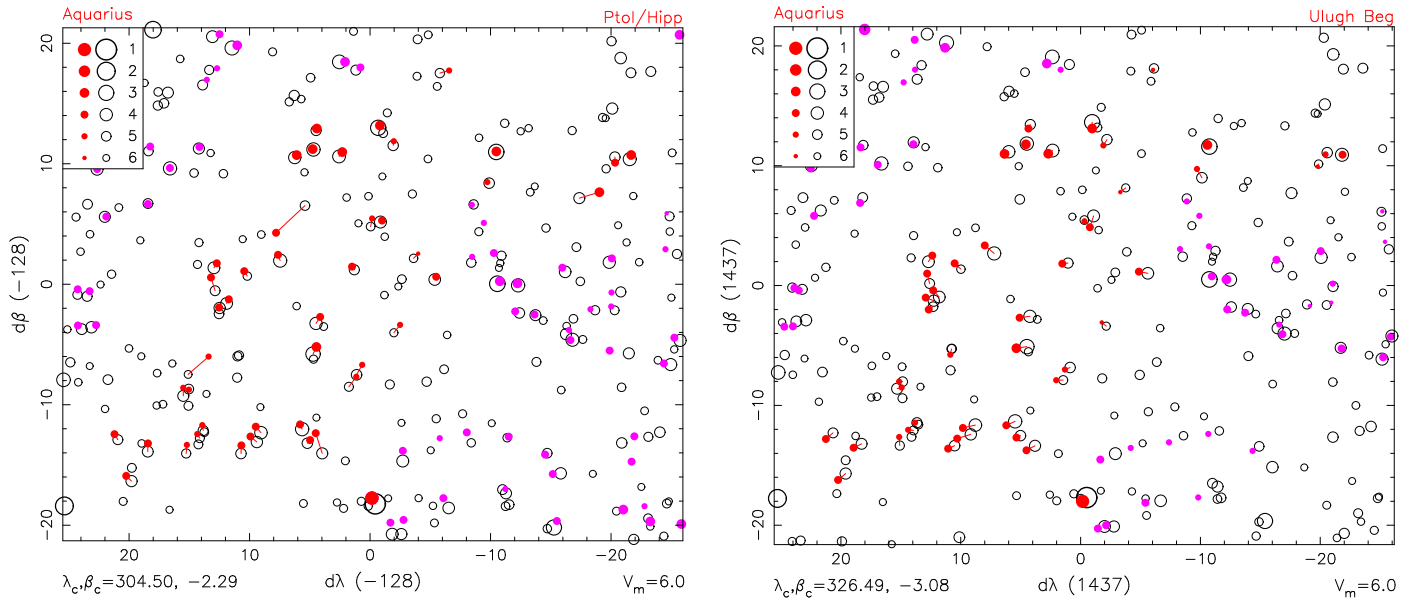
Figure B.33. Aquarius
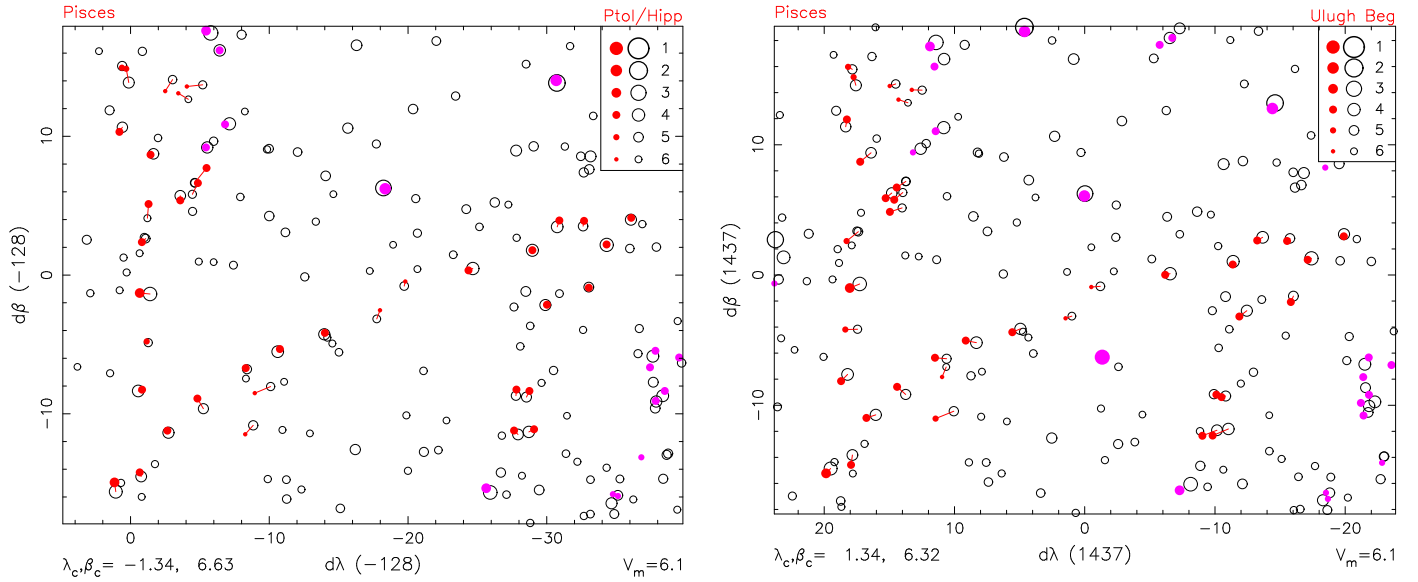
Figure B.34. Pisces
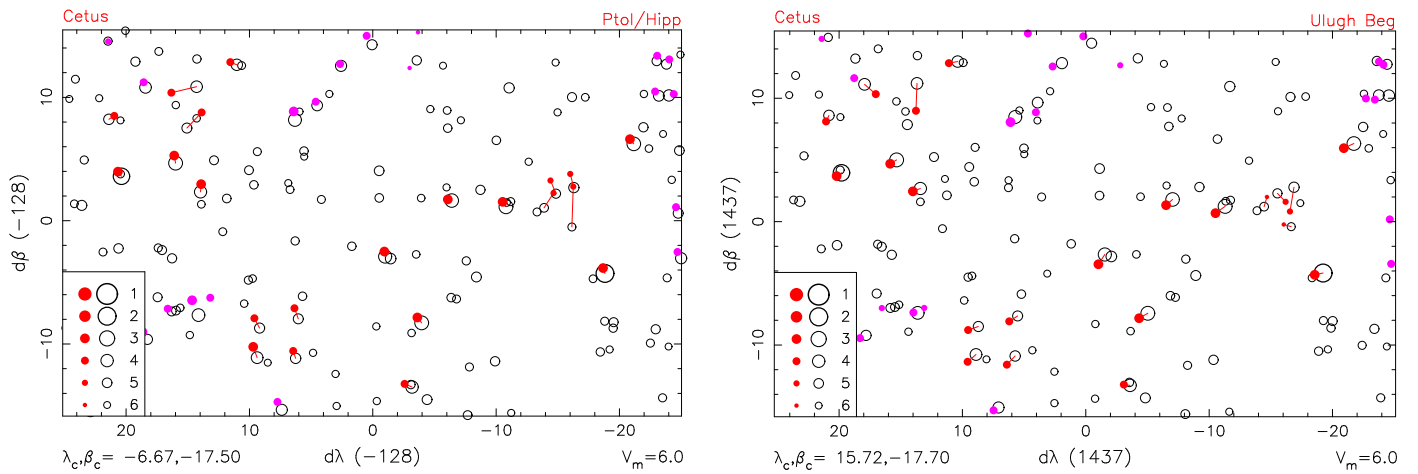
Figure B.35. Cetus
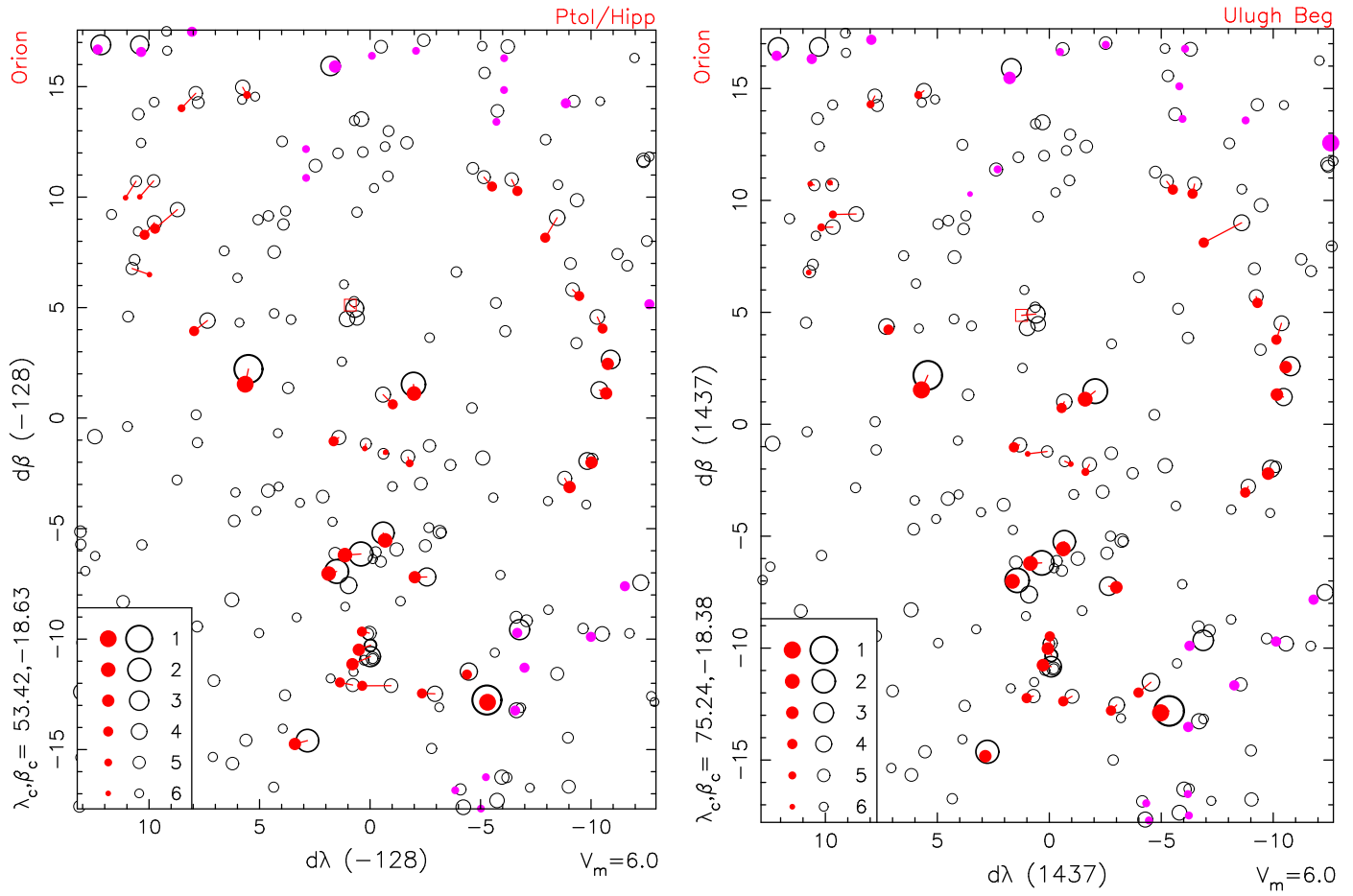
Figure B.36. Orion
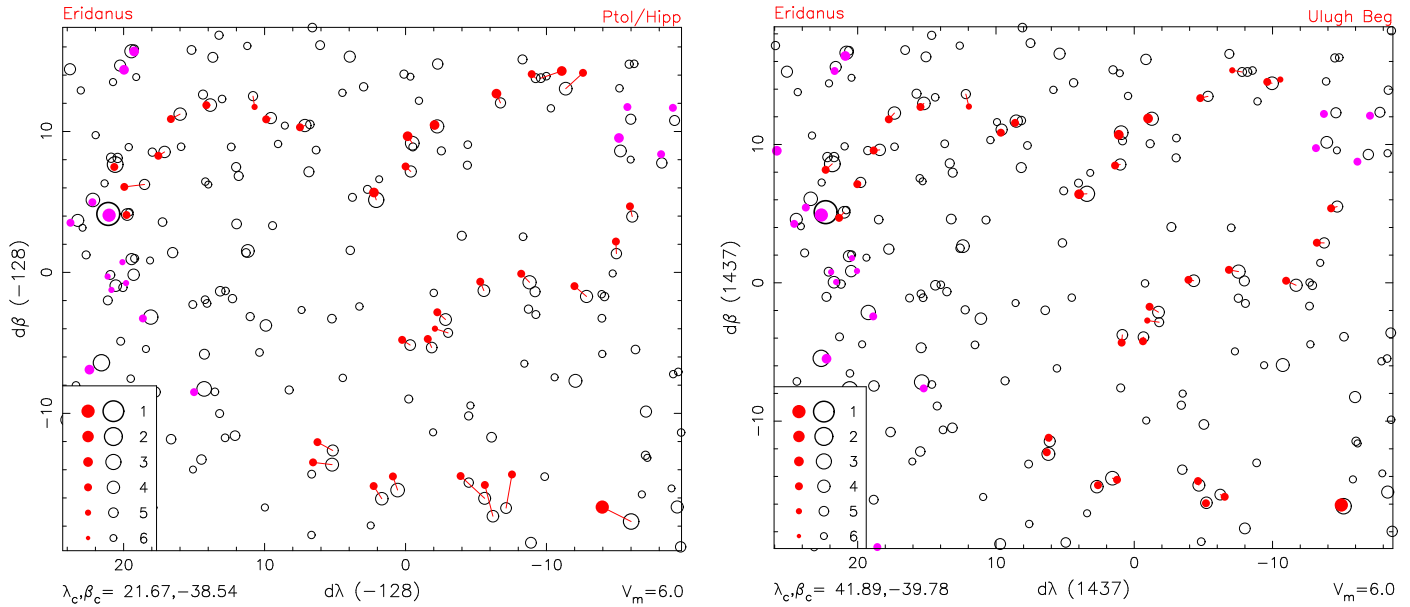
Figure B.37. Eridanus
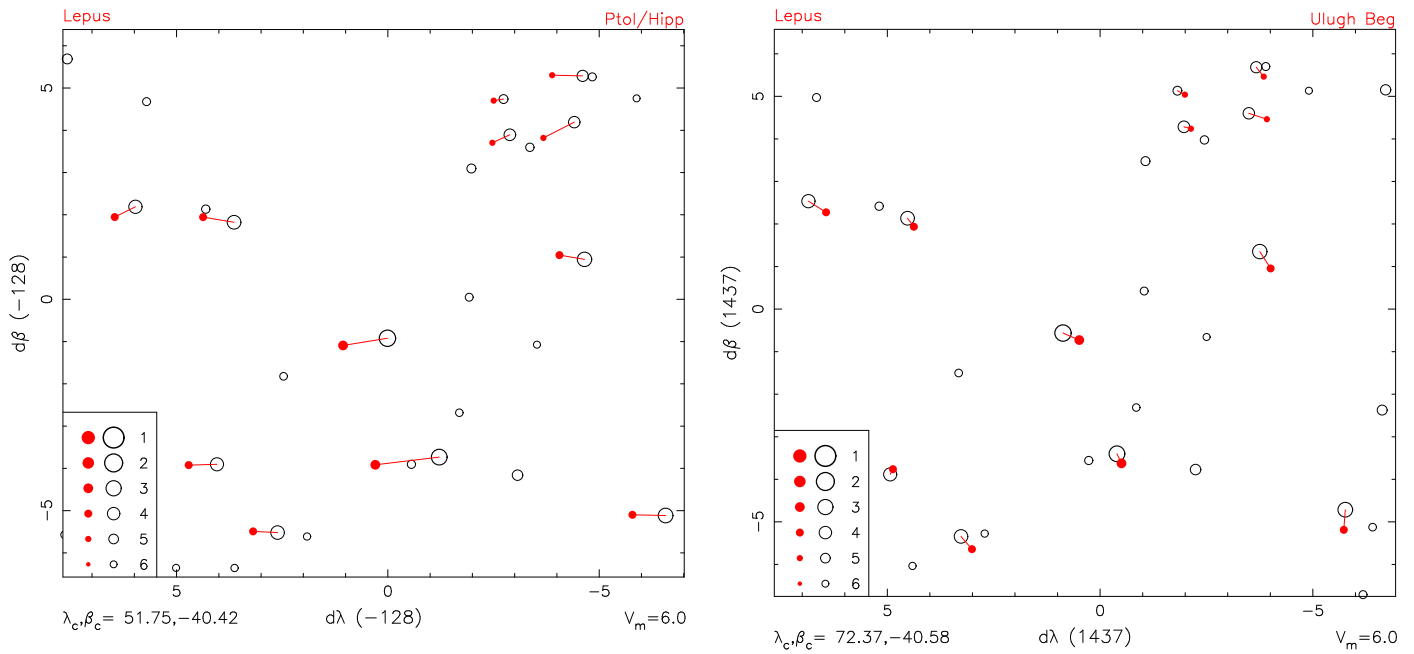
Figure B.38. Lepus
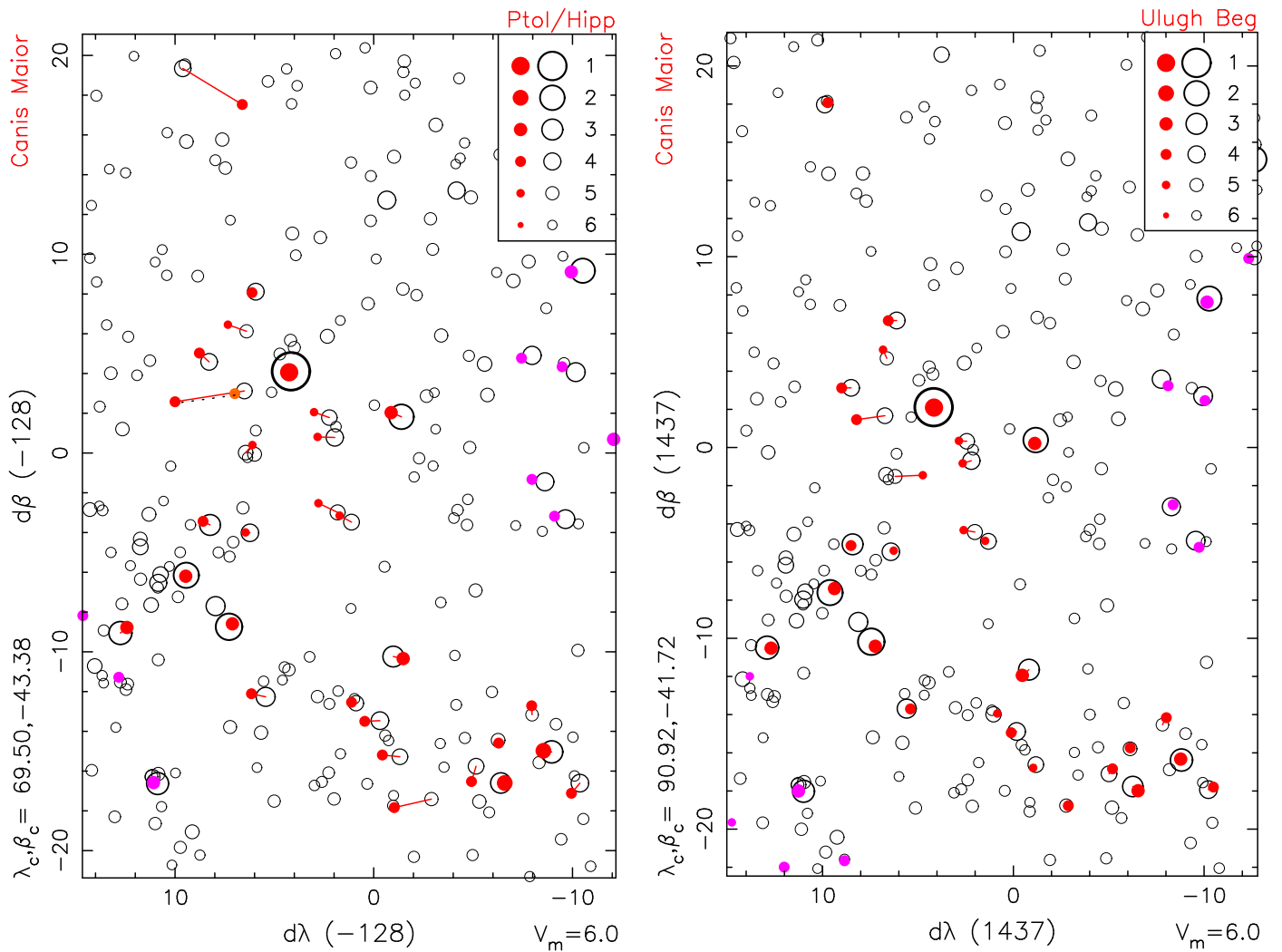
Figure B.39. Canis Maior
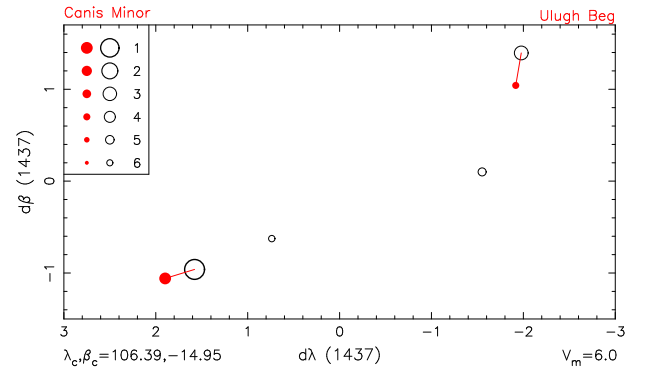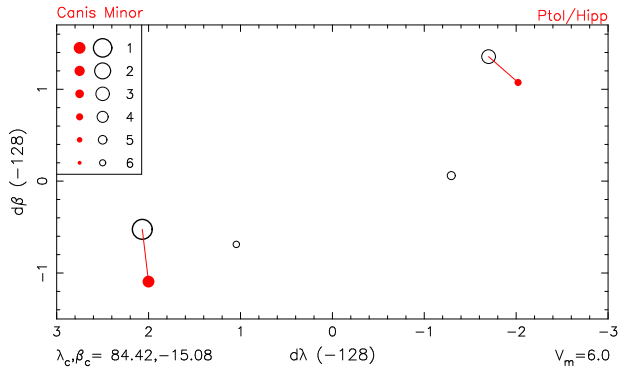
Figure B.40. Canis Minor
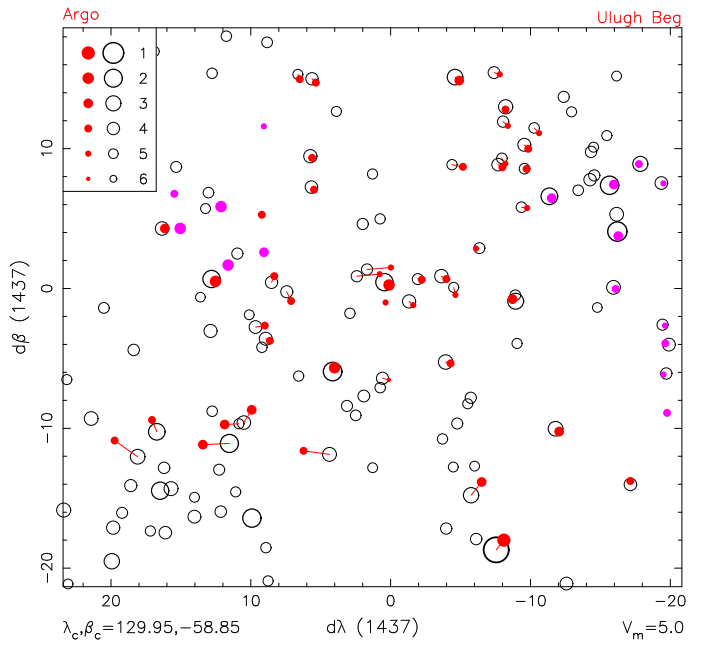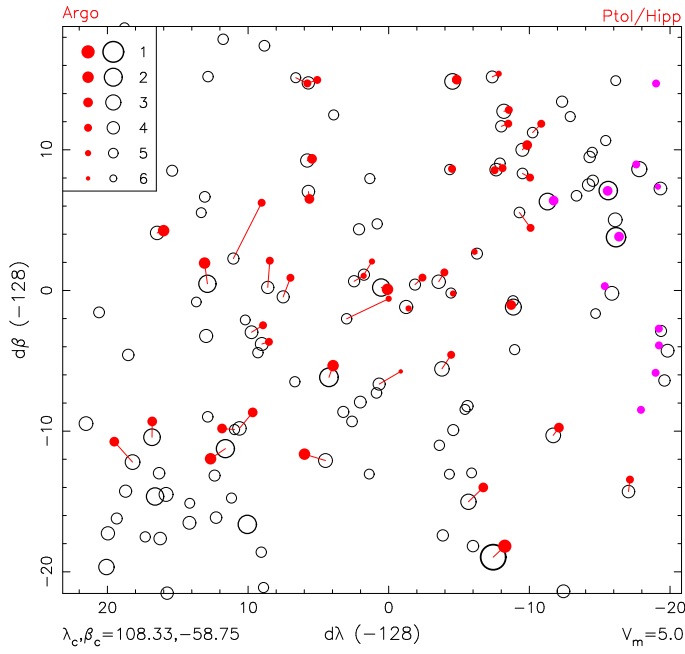
Figure B.41. Argo: bright Hipparcos stars only
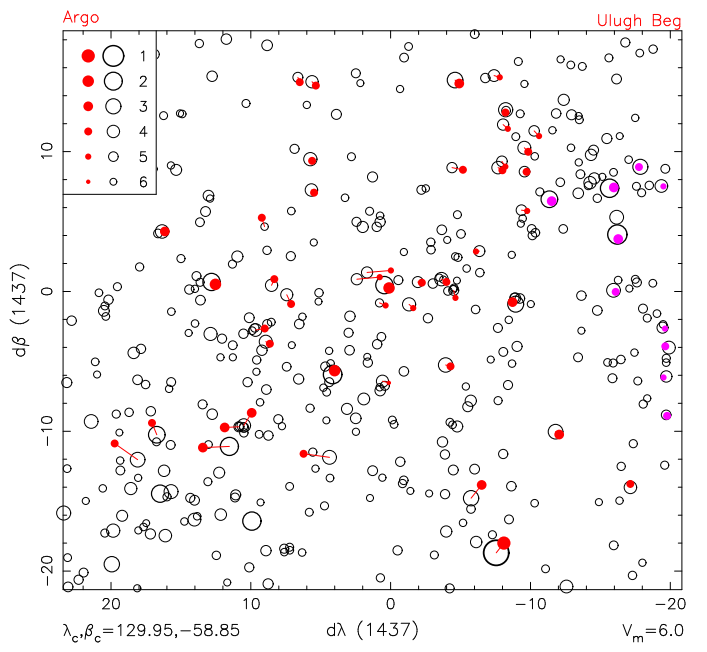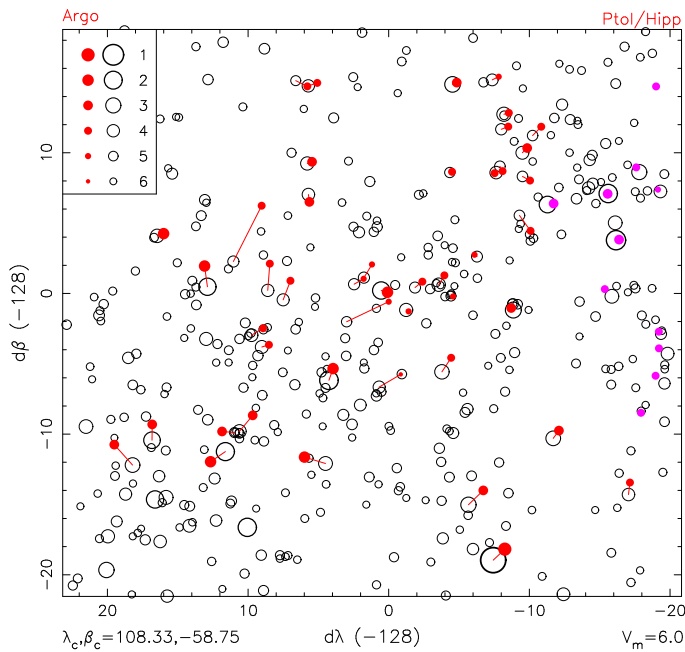
Figure B.42. Argo
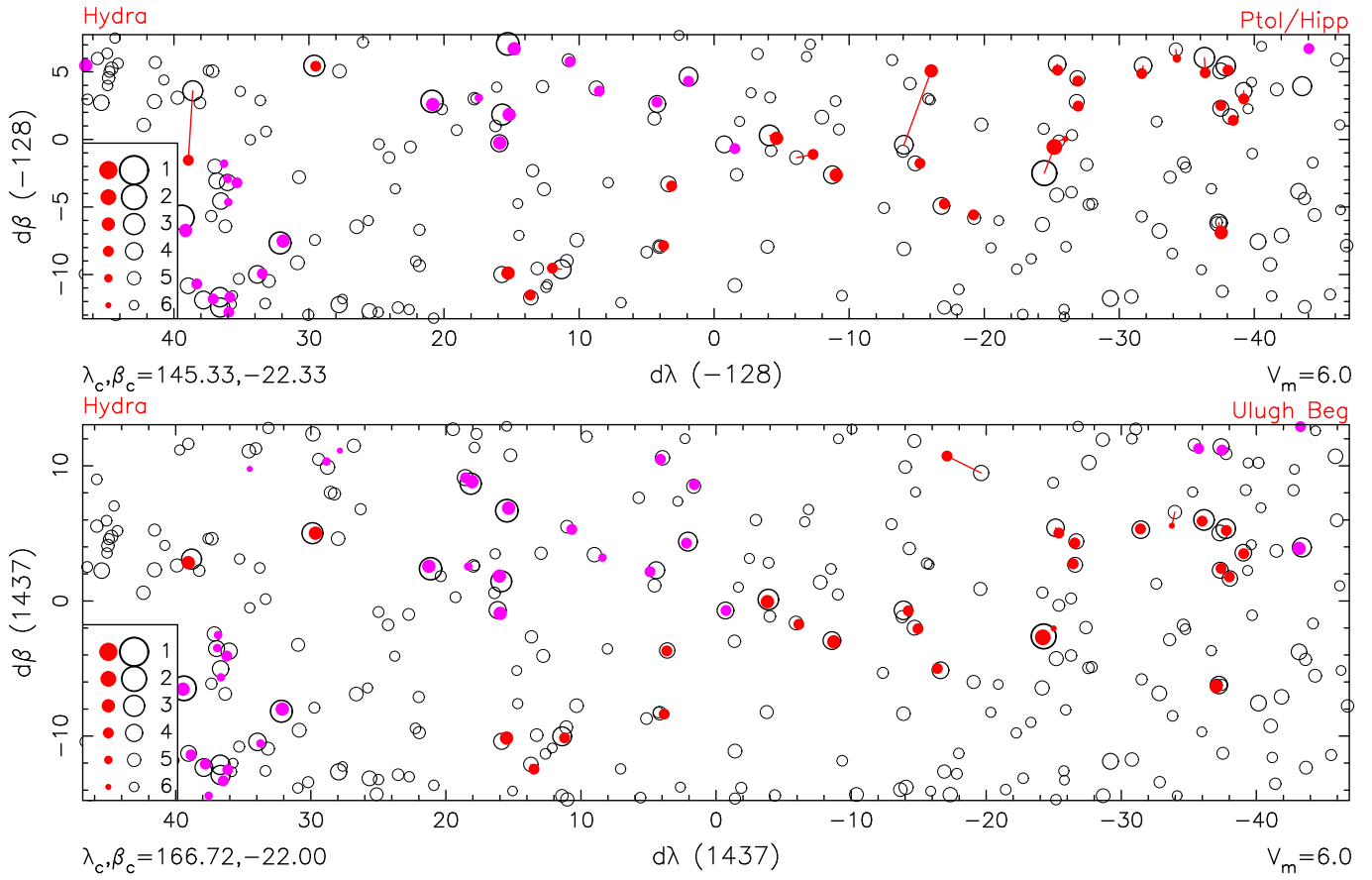
Figure B.43. Hydra
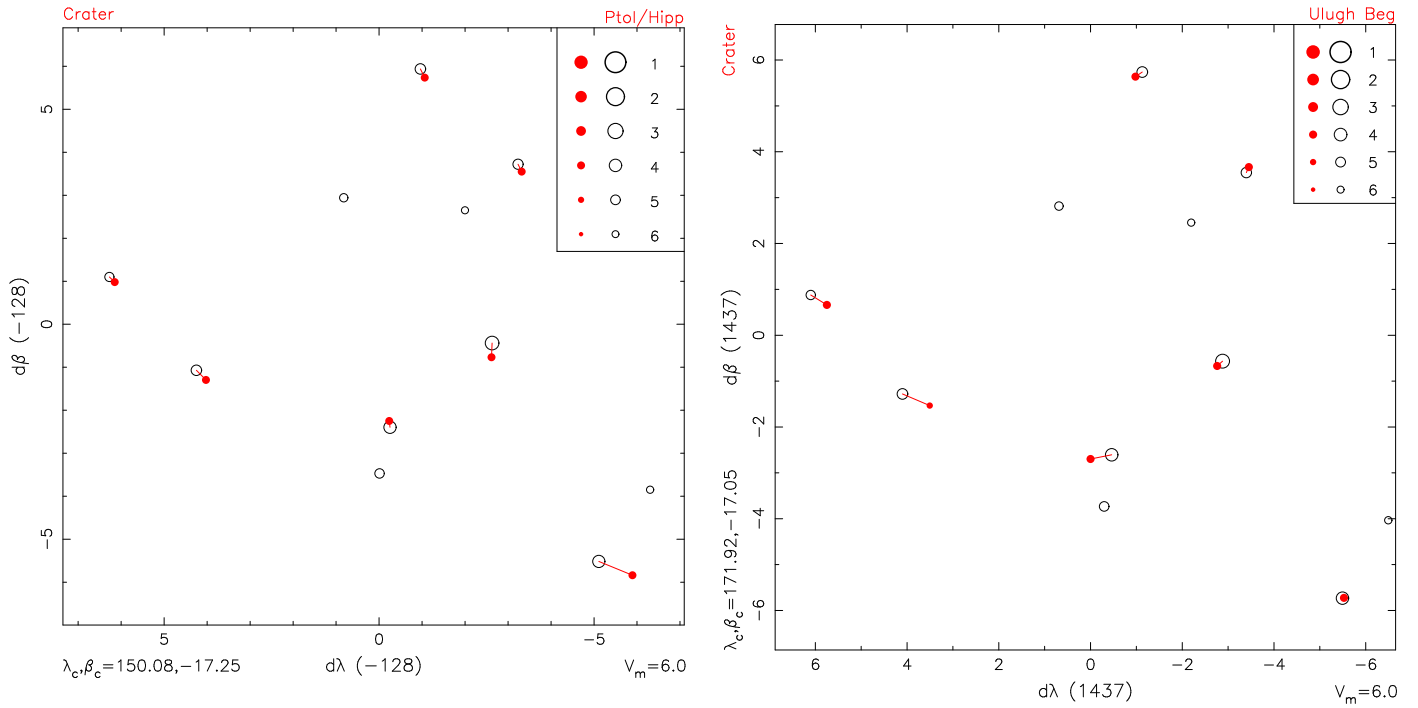
Figure B.44. Crater
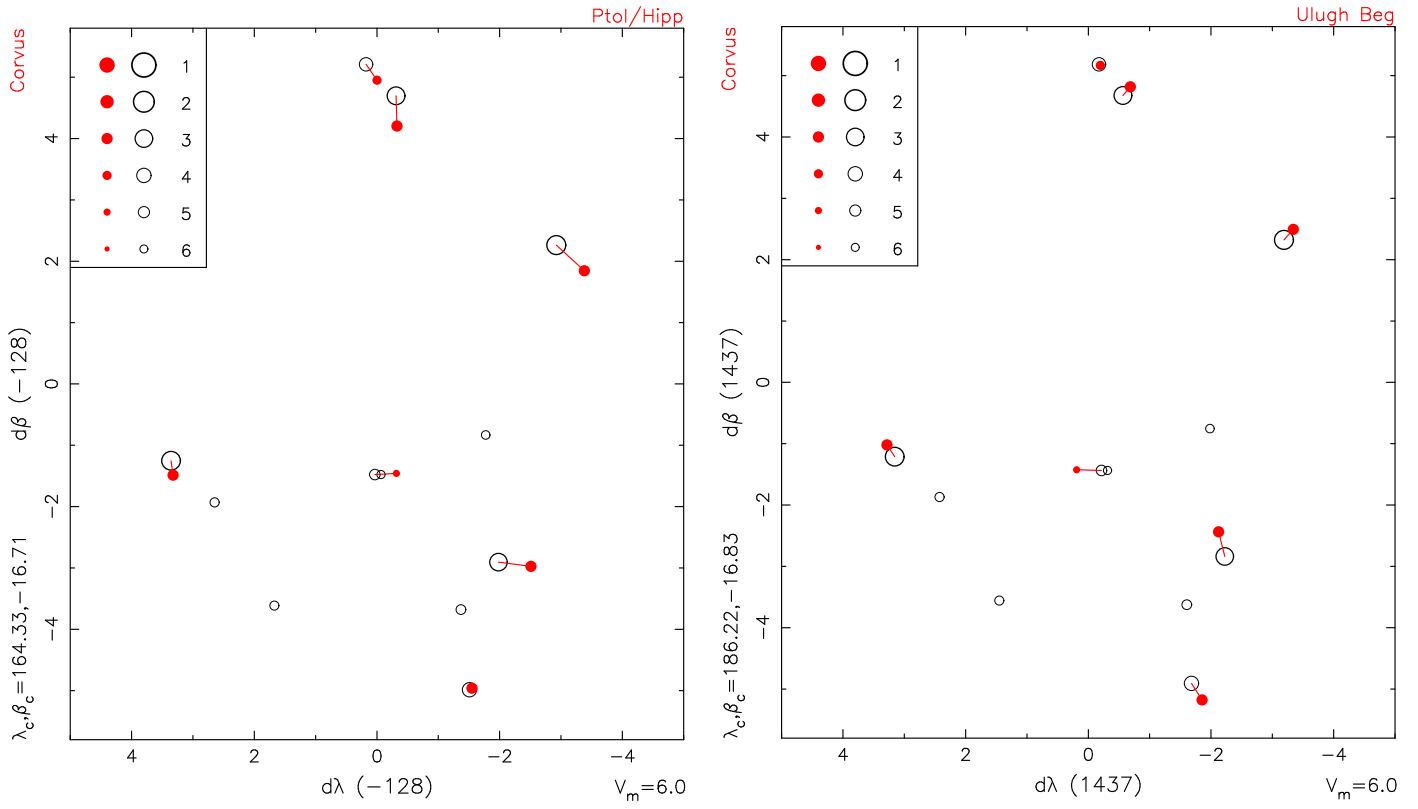
Figure B.45. Corvus
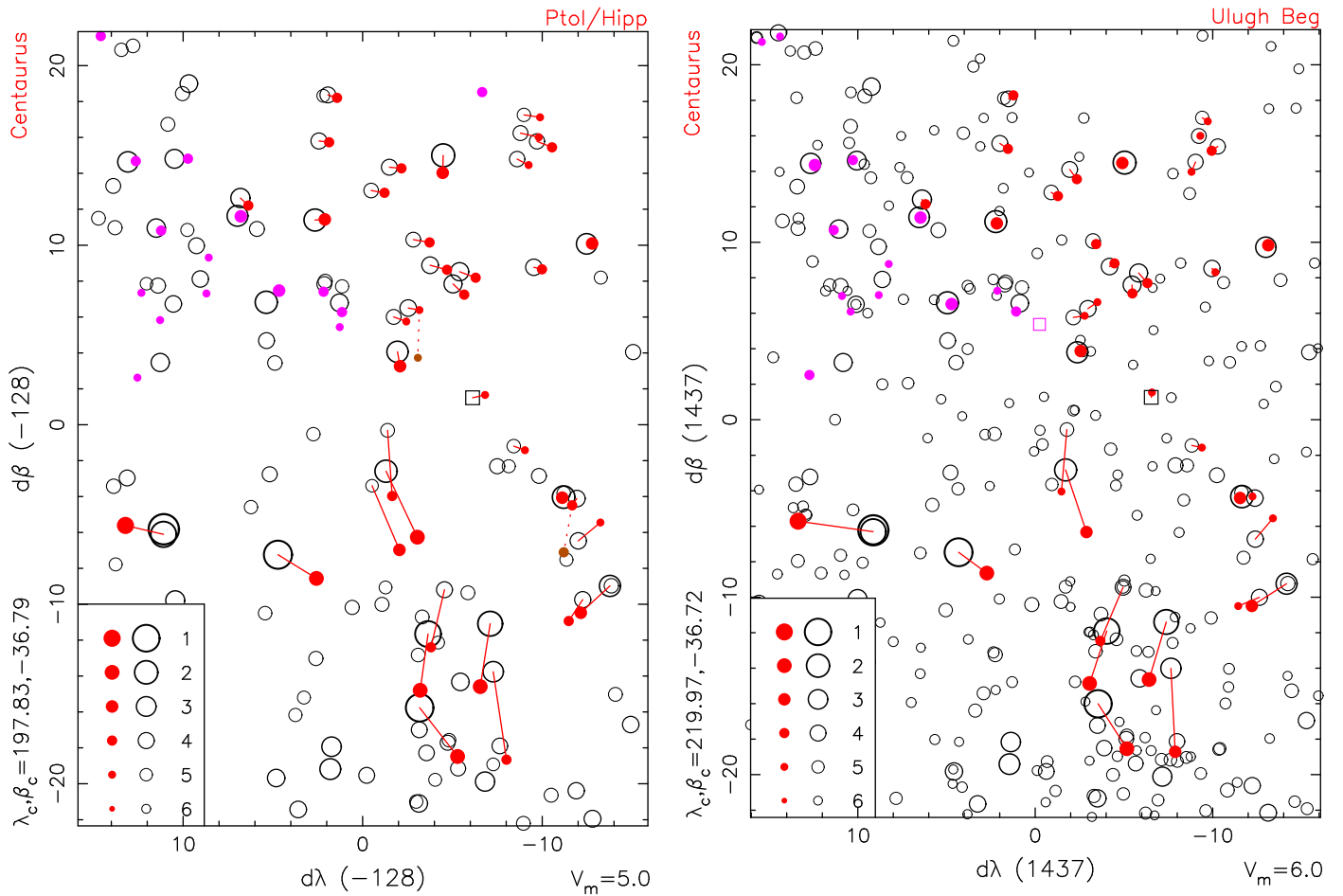
Figure B.46. Centaurus. In the plot for *Ptolemaios* only bright Hipparcos stars are shown. ω Cen is indicated near −8,2 with □
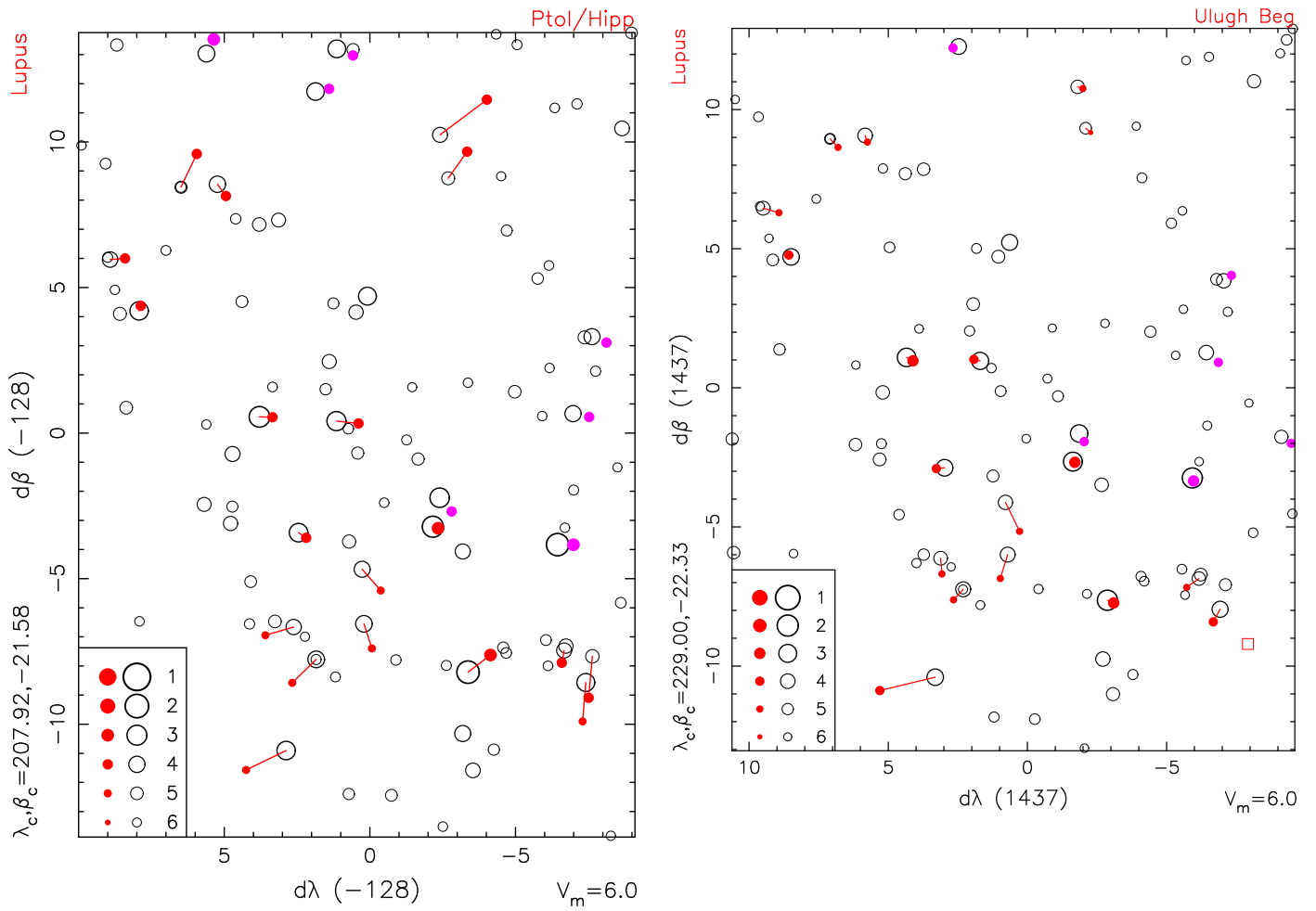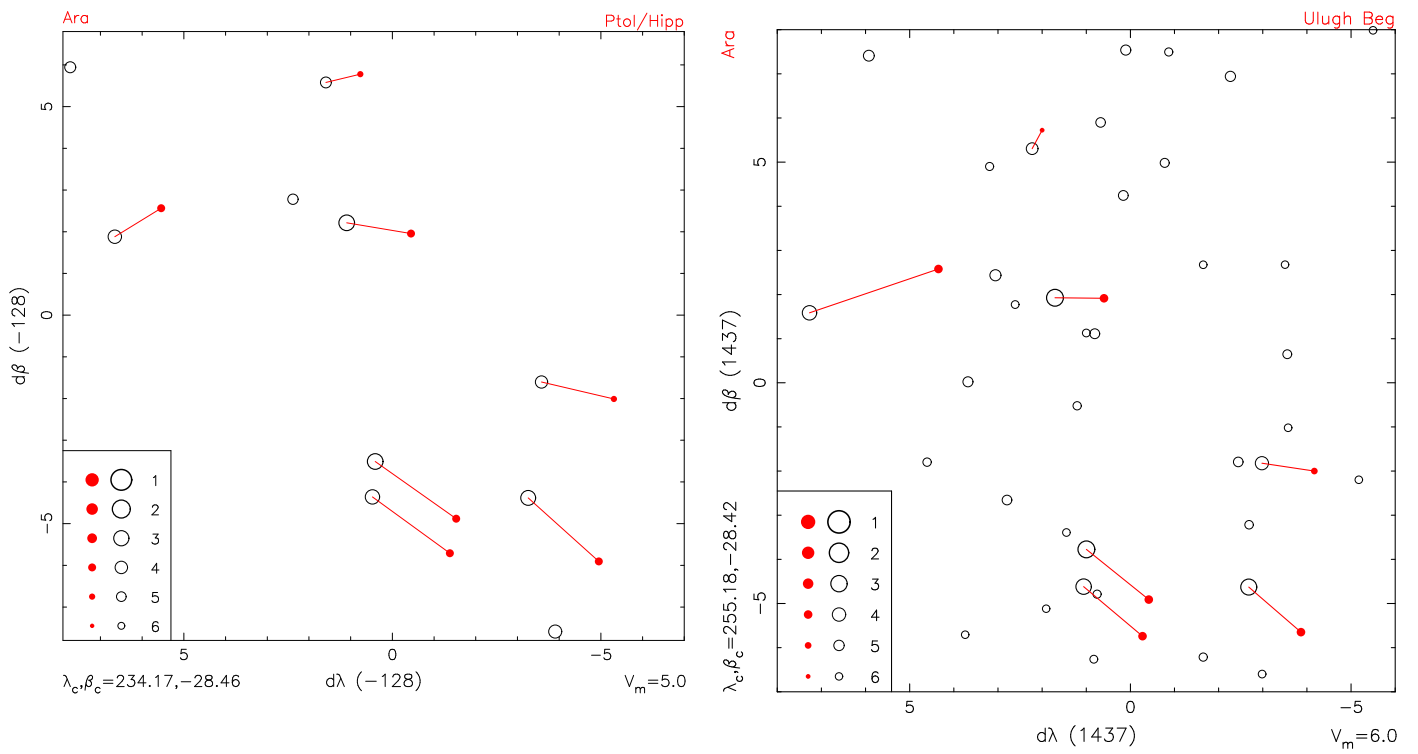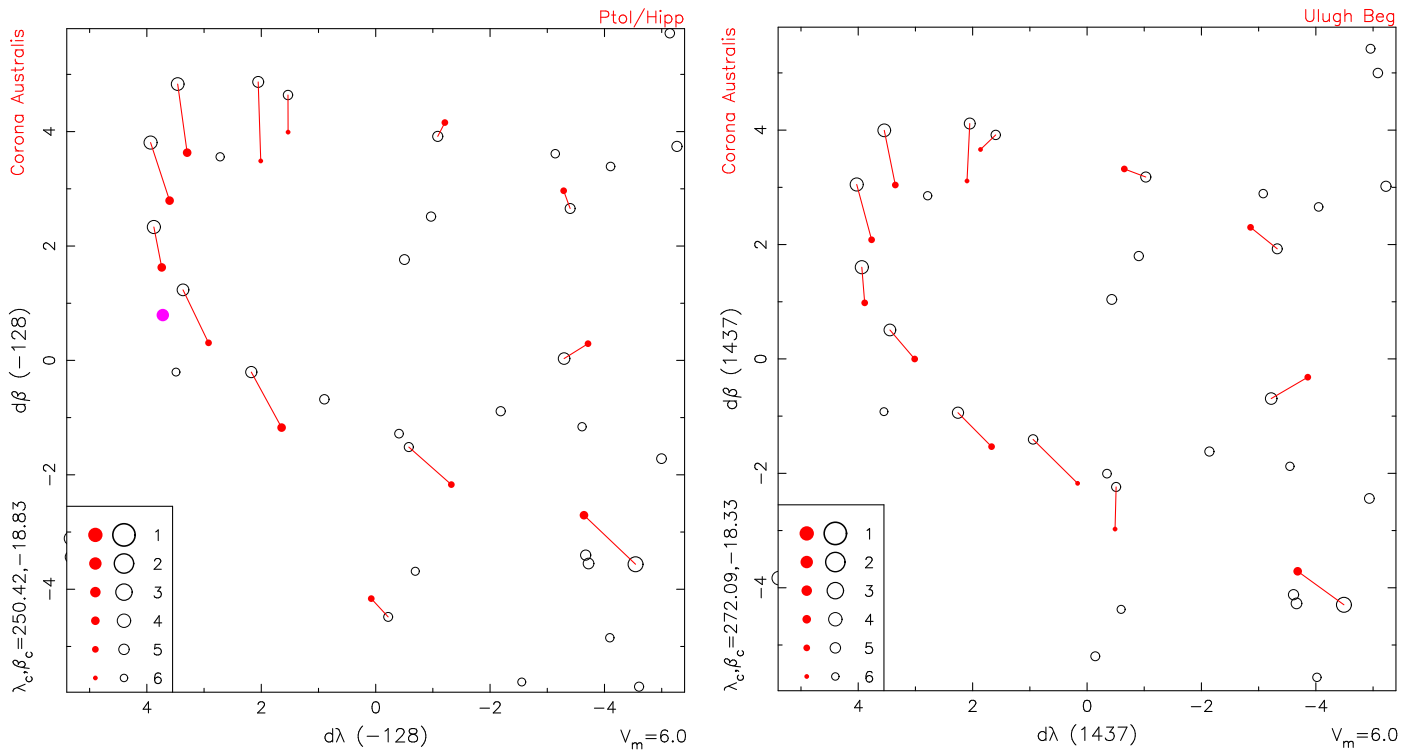
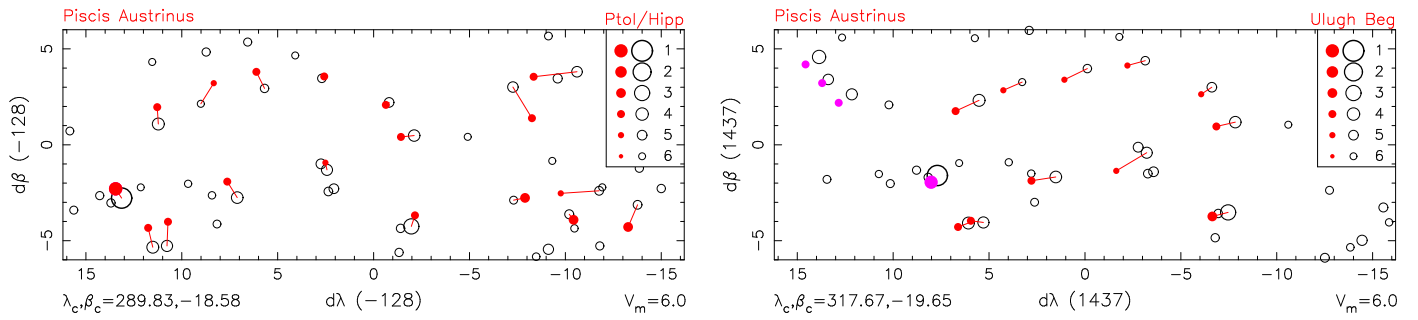**Figure B.47.** Lupus

Figure B.48. Ara

Figure B.49. Corona Australis

Figure B.50. Piscis Austrinus