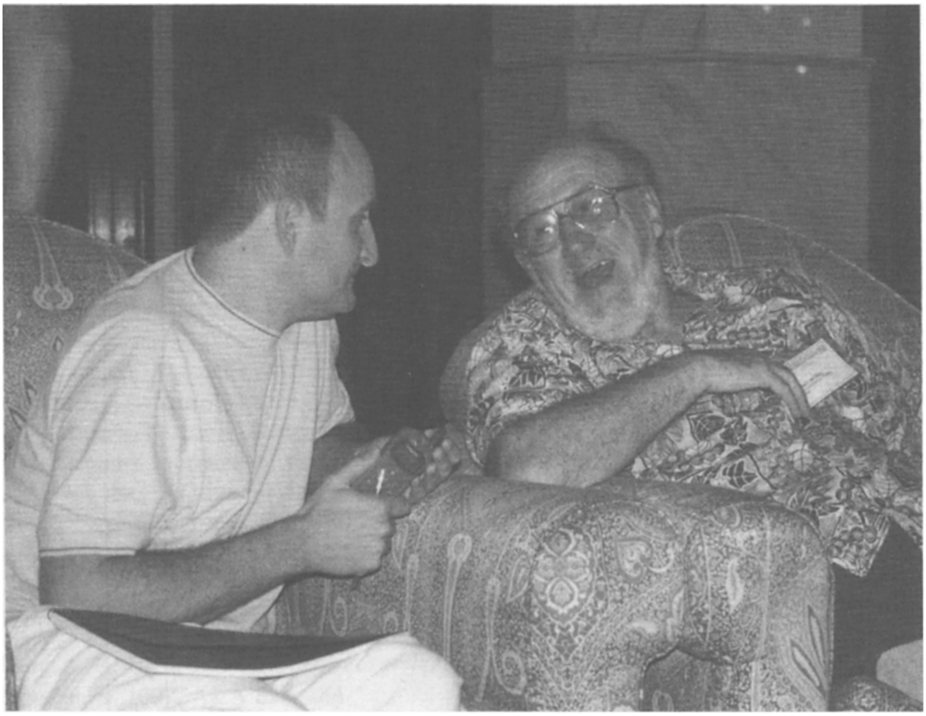
Part 3

Location and Distribution of Massive Stars



César Esteban and Peter Conti half-way. So far, so good

A Massive Star Odyssey, from Main Sequence to Supernova
Proceedings IAU Symposium No. 212, © *2003 IAU*
K.A. van der Hucht, A. Herrero & C. Esteban, eds.

Distribution of star-forming complexes and the structure of our Galaxy

Delphine Russeil

Laboratoire d'Astrophysique de Marseille, Observatoire de Marseille,
2 place Le Verrier, F-13004 Marseille, la France

Abstract. The determination of the external galaxies morphology is generally based on their appearance on optical images. At these wavelengths young stellar population and their associated H II regions, which can be grouped into star-forming complexes, appear preferentially located along spiral arms. Hence, it is naturally to use the same tracers to delineate the arms of our own Galaxy. But, where for external galaxies the distribution of star-forming complexes along the spiral arms is generally evident from direct imaging, for our Galaxy the spiral arms are strung out along the line of sight, leading to the superposition and mixing of information from the different complexes in the spiral arms making it difficult to distinguish them. Thus to access to the spatial distribution of young objects, hence to the large scale structure of our Galaxy, it is required first to identify and collect star-forming complexes (molecular clouds – H II regions – OB stars) and then to determine their distance. In this framework I review the observational results and difficulties concerning the distribution of star-forming complexes and the determination of the structure of our Galaxy.

1. Spiral arms and young stars

It is noted that ~80 % of the luminous galaxies exhibit spiral morphology. The classification of galaxy morphology is generally based on their appearance on *UBV*-images. At these wavebands young stellar population is prominent and appears preferentially located along the spiral arms (*e.g.*, *B*-image of NGC 1232); while when the galaxies are viewed in the redder light, characteristic of old, low-mass stars, the spiral structure is less pronounced.

Then it appears that spiral arms are the concentration of ongoing star formation (*e.g.*, Hodge & Kennicutt 1983; Considère & Athanassoula 1982, 1988) while older stars have drift out spiral pattern. In parallel, it is well established that molecular clouds are the principal sites of active star formation (Zuckerman & Palmer 1974; Burton 1976). It are the young massive stars formed in giant molecular clouds which due to their high luminosity ionize their environment, creating H II regions and rendering the arms very luminous respectively to the rest of the disk. These H II regions through their Hα and radio recombination lines makes these wavelengths very common to study Galactic morphology and kinematics. In parallel, the molecular material, through the CO emission, appears also more confined in the arms. Indeed, in M 31, for example, Loinard *et al.* (1999) show that the overall structure of the CO emission is fairly similar to that of the H I, IR (100 μm) and H II regions. Also, UV counterparts are observed in arms along which OB associations are distributed (Loinard *et al.* 1999). In the same way, in M 100 a good correlation is noted between massive star formation, traced by the ionized gas radio (5 GHz) emission (not affected by extinction) and the molecular gas (García-Burillo *et al.* 1998).

Hence, the external galaxies show us that the main tracers of the spiral arms are the massive star formation regions, which can be probed through different sources: the hot massive stars (O,B stars), the ionized gas (H II regions and diffuse ionized gas) and molecular clouds. But two important remarks must be underlined to understand afterwards the difficulties encountered with the determination of our own Galaxy structure:
(*i*) arms distortions, arm splitting, bridges, branching, *etc*, are very common in spiral galaxies (*e.g.*, Kennicutt 1981) in the Hubble Atlas of Galaxies (Sandage 1961); and
(*ii*) the spiral structure of external galaxies is mainly traced by the most massive molecular clouds and the brightest H II regions (*e.g.*, Baade 1963; Rumstay & Kaufman 1983; Boulanger *et al.* 1981) as we can note on the Hα image of NGC 3359 (Rozas, Zurita & Beckman 2000).

As suggested by external galaxies, it appears natural to use the same tracers to lead the study of our Galactic arms design. But, in practice, if for external galaxies, the distribution of star-forming regions along the spiral arms is generally evident from direct imaging, for our Galaxy, due to our location inside it, the arms are strung out along the line of sight, leading to the superposition and mixing of information from the star-forming regions located in different arms, making difficult their distinction. Hence, the study of the large scale structure of our Galaxy is based on the distance determination of tracers. Mainly two ways are followed to such distance determination: the spectro-photometric distance of the massive stars or the kinematic distance of their associated gas.

2. Distance of stellar tracers

Historically, the first way to probe the structure of our Galaxy was to use the bright candles which the bright hot stars are. In this way Morgan and co-workers (Morgan *et al.* 1952, 1953) provided the first evidence for spiral structure. But, as pointed out by Walborn (1973), if stellar distance is the best estimation of star-forming region, it is sullied with several sources of uncertainties which limits its accuracy. Moreover, from the point of view of the Galactic structure, the most interesting H II regions are the farthest. But, they are regions for which exciting stars are not well known because of their large magnitude. One can enumerate the three main sources of stellar distance uncertainties:
(*i*) uncertainty on the identification of the stars ionizing the H II region;
(*ii*) uncertainty of the absolute magnitude - spectral type calibration (it is the major source of uncertainty). Comparing calibration from different authors (*e.g.*, Schmidt-Kaler 1983; Walborn 1972; Balona & Crampton 1974; Turner 1980; Vacca *et al.* 1996), one usually notes difference on absolute magnitude of more than 0.5 mag. Such uncertainty induces a distance inaccuracy of 25%; and
(*iii*) uncertainty on the spectral type determination. For a given calibration, any mistake on the spectral type induces an uncertainty which can reach 1 mag corresponding to a distance uncertainty of 50 %.

Hence, still today there is a significant error (± 25 %) in the spectrophotometric distance of an individual star (*e.g.*, Humphreys 1976; Kaltcheva & Hilditch 2000) and the resulting scatter tends to blur the major features. For this reason, stars were checked for membership in stellar associations, clusters and H II regions. The distance to such a stellar group will be more accurate, since it represents an average for many stars and permits to precise the arm drawing. This aspect is well illustrated by figures 1 and 2 of Humphreys (1970). Finally, let us note that, due to interstellar extinction, spectro-photometric data are limited to distance from the Sun of about 4 kpc on the average, allowing to probe only the local structures. In this framework, restricted to a region within a few kiloparsecs from the Sun, the stellar spiral-structure diagrams (*e.g.*, Crampton & Georgelin 1975; Vogt & Moffat 1975; Bok & Bok 1978; Mel'nik & Efremov 1995) always show three basic features: the Sagittarius arm ($l = 340° - 30°$) around 2 kpc from the Sun, the local arm, the Perseus arm ($l = 100° - 150°$) at 2 to 3 kpc and the Carina arm ($l = 280° - 300°$).

3. Kinematic distance of tracers

An alternative to the stellar distance is to use velocity information to determine the kinematic distance. Indeed, as for external galaxies, hot massive young stars are expected to be associated to molecular clouds and induce H II regions. Hence ionized hydrogen recombination lines (H109α, H110α , Hα), molecular lines (CO lines) and absorption lines (*e.g.*, H_2CO, OH) are usually used to determine the kinematic distance. The radio lines, due to their non sensitivity to interstellar extinction, allow to probe almost the whole Galactic plane.

The kinematic distance calculation assumes the object on circular orbit around the Galactic Center and requires to know the Galactic rotation curve. But circular rotation departures are commonly noted for both stars and gas (Humphreys 1970, 1972; Burton 1976). The presence of such noncircular motions in the spiral arms severely limits the accuracy of any kinematic distance. In particular, velocity anomalies in the Perseus and Carina arms are known for a long time (Rickard 1968; Humphreys 1970, 1972); more recently, Álvarez, May & Bronfman (1990) have shown velocity excess of 12 km s^{-1} in the Carina arm and Heyer & Terebey (1998) show evidence of expanding motions in the Perseus arm.

In parallel, the knowledge of the rotation curve is essential to transform the radial velocities to distances, but its choice is not obvious as, depending on the authors, it is determined from observations of various tracers (see Table 1) and from restricted Galactic directions, hence inevitably biased by direction dependent irregularities. One can recall that in addition to stellar distance uncertainty dependency (Turbide & Moffat 1993), the outer Galaxy is always incompletely covered leading to large scatter and error bars (Binney & Dehnen 1997). These uncertainties make difficult the identification of the irregularities and the determination of the general rotation curve shape.

In addition, any change on the solar parameters $R_\odot$ and $\theta_\odot$ will affect the kinematic distance determination. Indeed, any change on $\theta_\odot$ will modify the slope of the rotation curve, while a change on $R_\odot$ will mainly affect the radial scaling. Actually, several authors suggest $\theta_\odot \approx 200$ km s^{-1} and $R_\odot < 8$ kpc

Table 1. Some recent rotation curves of our Galaxy.

reference	zone	objects
Sinha 1978	quad. I and IV	H I
Burton & Gordon 1978	quad. I	H I , CO
Gunn *et al.* 1979	quad. I	H I
Clemens 1985	North	CO, H I for $R < R_\odot$ CO, H II for $R > R_\odot$
Rohlfs *et al.* 1986	North + South	H I for $R < R_\odot$ H II for $R > R_\odot$
Fich *et al.* 1989	North	H I , CO-H II
Alvarez *et al.* 1990	quad. IV	CO
Merrifield 1992	ext. gal.	H I
Brand & Blitz 1993	all	H II -CO, H I reflection neb.

(Brand & Blitz 1993; Dambis *et al.* 1995; Olling & Merrifield 1998), while the usual adopted values are 220 km s^{-1} and 8.5 kpc.

An other limitation on the kinematic distance determination comes from the distance ambiguity problem: for inner parts of the Galaxy the rotation model gives two possible distances for a given observed velocity; it implies to choose between the near and far distance. In practice this choice requires multi-wavelength and geometrical considerations. Finally, one can note that the kinematic distance is unreliable at low Galactic longitudes because of velocity degeneracy.

Such kinematic distance approach was initially applied to radio emission of H II regions (Mezger 1970; Downes *et al.* 1980). In this way Caswell & Haynes (1987) investigated H II region distribution in the 4th Galactic quadrant. They detect H II regions up to 20 kpc outlining the Carina, Crux and Norma arms. Some authors concentrate on molecular clouds. For example, Cohen *et al.* (1985) show the Carina arm is well outlined by giant molecular clouds ($M > 10^5\,M_\odot$); these clouds trace this arm over more than 20 kpc from the Sun. They traced also the Sagittarius and Perseus arms. In addition to trace arms, Solomon & Rivolo (1989), from a sample of 440 molecular clouds of the Northern hemisphere, show the cooler clouds ($5\,K < T_{\rm peak} < 7.5\,K$) of their sample clearly exhibit less confinement to the arms than the warmer ($T_{\rm peak} > 7.5\,K$). Giant molecular clouds are clearly present in the inter-arm cloud population, although they are statistically less massive than the arm population; a fact already mentioned for external galaxies.

4. Star forming complexes distribution

A last method to investigate the large scale pattern of our Galaxy is to group physically the different young sources (H II regions, molecular cloud, exciting stars and OB clusters) into star-forming complexes (Figure 1).

This method allows the minimization, for a given complex, of the velocity and distance spread which are caused principally by bulk gas motions and stellar

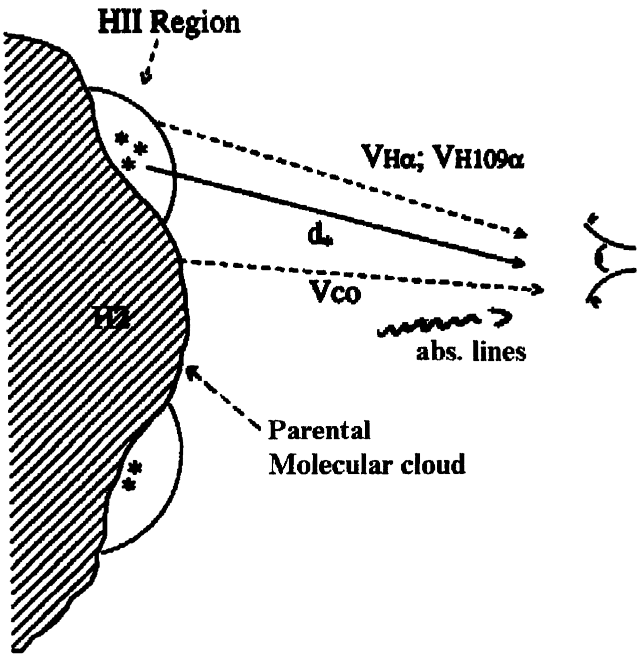


Figure 1. Schematic view of a star forming complex and corresponding observable information.

distance uncertainties. This strategy, ignited by Bok (1971), has been applied by Georgelin & Georgelin (1976) to trace the 4-arm spiral pattern of our Galaxy. As it is well established that massive young stars and their associated H II region born and evolve from giant molecular clouds, it is expected that different H II regions belonging to the same complex are spatially and kinematically grouped around a parental molecular cloud. Actually, groupings are based mainly on similar velocity, similar stellar distance and spatial proximity and/or connection by diffuse hydrogen components. The complex systemic velocity separation is done through identifying the gas motions. Then a star-forming complex can be seen as the grouping of several ionized and molecular sources.

In this framework, the Georgelin & Georgelin model (1976) combined optical observations (distances of exciting stars and Hα radial velocities) with radio observations of H II regions (H109α radial velocities from Mezger 1970) and absorption lines velocity to show that the distribution of star-forming complexes outlined a four-segment model (Figure 2).

We have redone such study adding small to large scale multi-wavelength information. Especially, we collected from literature updated and new data about velocity of H II regions (*e.g.*, Downes *et al.* 1980; Caswell & Haynes 1987; Fich *et al.* 1990), molecular material (*e.g.*, Dame *et al.* 1986; Grabelsky *et al.* 1988; Sodroski 1991; Blitz, Fich & Stark 1982; Jacq, Despois & Baudry 1988; Dame & Thaddeus 1985) and absorption lines (Downes *et al.* 1980). We updated and homogenized stellar distance of H II region exciting stars. But the most impor-

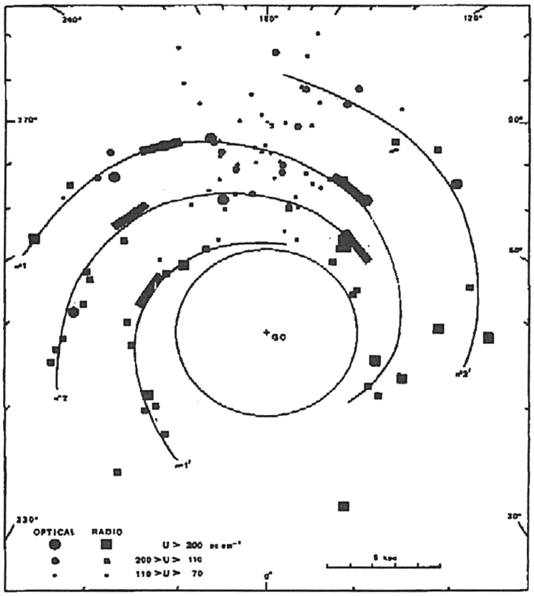


Figure 2. Spiral model of our Galaxy obtained from high-excitation parameter H II regions ($U > 70\,\mathrm{pc\,cm^{-2}}$) by Georgelin & Georgelin (1976). The arm identification is 1: the Sagittarius-Carina arm, 2: Scutum-Crux arm, 1': Norma arm and 2': Perseus arm.

tant improvement comes from the Marseille Hα survey (MHS hereafter) which allows us to access to velocity information of the Hα emission of the ionized gas. Let us describe briefly this survey. The MHS uses a 36 cm telescope equipped with a scanning Fabry-Perot interferometer and a photon counting camera. This instrument is described by le Coarer *et al.* (1992) and the data reduction method by Georgelin *et al.* (1994). It allows us to have spectral information continuously all over the observed field and to separate nebular components from the night-sky lines. The nebular Hα profiles observed are always very complex. They are composed of the ensemble of emission lines coming from each emitting layer along the line of sight, each with a potentially different velocity. The Hα information is essential to perform the sources grouping into complexes, to identify the internal motions of H II regions and to solve the distance ambiguity (*e.g.*, Georgelin *et al.* 2000). Lot of H II regions, up to now only detected in radio wavelength, have been detected in Hα from the MHS. In addition to the bright H II regions, a large fraction of the ionized hydrogen is observed as diffuse layers known as the Warm Interstellar Medium (Reynolds 1983). This diffuse emissions exhibit similar velocity as discrete H II regions suggesting also it is rather located along the arms; sometimes it is the only arm tracer (Russeil 1997).

We then established a new catalogue of star-forming complexes. The distribution of these complexes projected on the Galactic plane allows the study of the large scale pattern of our Galaxy. Adopting a 4-arm model, the new data shows similar result as Georgelin and Georgelin (1976), but arm design and ex-

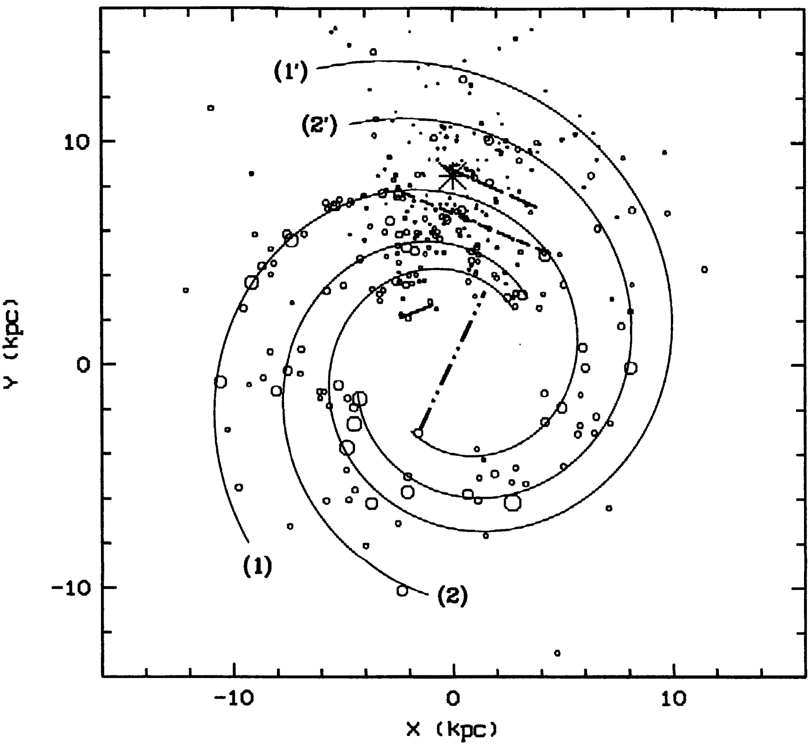


Figure 3. Revised model of our Galaxy, obtained by Russeil (2003). The symbol size is proportional to the excitation parameter. The Sun position is given by the big star symbol. All the complexes are plotted. We have also schematized the local arm feature (long dashed line), the bar orientation and length (dashed-dot-dot line) from Englemaier & Gerhard (1999), the expected departure from logaritmic spiral arm observed for the Sagittarius-Carina arm (short dashed line) and finally feature probably linked to the 3 kpc arm (solid line). The arm identification is 1: the Sagittarius-Carina arm, 2: Scutum-Crux arm, 1': Norma-Cygnus arm and 2': Perseus arm. Same scale as Figure 1.

tension are now precised and the known length of the arms is doubled. In this updated model (Figure 3) one can identify the Sagittarius-Carina arm (1), the Scutum-Crux arm (2) and the Perseus arm (2'), while the Norma and Cygnus arms appear as being the two extremities of a unique arm called Norma-Cygnus arm (1').

5. Conclusions and perspectives

We have shown that the study of the spiral structure of our Galaxy is intimately linked to our knowledge of young massive stars. The distance determination of these stars appears as the foundation of any kinematical and structural study of our Galaxy. Consequently, we discussed the sources of uncertainty on stellar and kinematic distances. Such uncertainties imply confusion of the arms delimitation. A strategy to decrease the uncertainty influence on arms tracing is to group the young objects. The first thing done was to look at the distribution of associations and young open clusters instead of individual young stars, the next step was to group young objects (H II regions, exciting stars and molecular clouds) into complexes. In this approach the velocity is essential to associate H II regions and their exciting stars to molecular clouds. But, still today, lot of H II regions have unknown stellar distance determination because exciting star(s) are not identified and/or spectroscopic and photometric data are not available. Moreover, for distant H II regions, exciting stars are not optically observable, because too faint or embedded. An alternative would be to derive the distance from IR observations (which are not affected by extinction) in order to determine the stellar distance of such H II regions.

References

Álvarez, M., May, J., Bronfman, L. 1990, ApJ 348, 495
Baade, W. 1963, J. Royal Astron. Soc. Canada 57, 232
Balona, L., Crampton, D. 1974, MNRAS 166, 203
Binney, J., Dehnen, W. 1997, MNRAS (Letters) 287, L5
Blitz, L., Fich, M., Stark, A.A. 1982, ApJS 49, 183
Bok, B.J. 1971, *Observational Evidence for Galactic Spiral Structure*, in: C. de Jager (ed.), IAU Highlights of Astronomy Vol. 2 (Dordrecht: Reidel), p. 63
Bok, B.J., Bok, P. 1978, *The Milky Way* (Cambridge: Harvard University Press)
Boulanger, F., Combes, F., Stark, A.A. 1981, A&A (Letters) 93, L1
Brand, J., Blitz, L. 1993, A&A 275, 67
Burton, W.B. 1976, Ann. Review Astron. Astrophys. 14, 275
Burton, W.B., Gordon, M. 1978, A&A 63, 7
Caswell, J.L., Haynes, R.F. 1987, A&A 171, 261
Clemens, D.P. 1985, ApJ 295, 422
Cohen, R.S., Grabelsky, D.A., May, J., Bronfman, L., Alvarez, H., Thaddeus, P., Bronfman, L. 1985, ApJ (Letters) 290, L15
Considère, S., Athanassoula, E. 1982, A&A 111, 28
Considère, S., Athanassoula, E. 1988, A&AS 76, 365
Crampton, D., Georgelin, Y.M. 1975, A&A 40, 317
Dambis, A.K., Mel'nik, A.M., Rastorguov, A.S. 1995, Pis'ma Astron. Zh. 21, 331 (= Astron. Letters 21, 291)
Dame, T.M., Elmegreen, B.G., Cohen, R.S., Thaddeus, P. 1986, ApJ 305, 892
Dame, T.M., Thaddeus, P. 1985, ApJ 297, 751
Downes, D., Wilson, T.L., Bieging, J., Wink, J. 1980, A&AS 40, 379
Englmaier, P., Gerhard, O. 1999, MNRAS 304, 512
Fich, M., Blitz, L., Stark, A.A. 1989, ApJ 342, 272
Fich, M., Dahl, G.P., Treffers, R.R. 1990, AJ 99, 622
García-Burillo, S., Sempere, M.J., Combes, F., Neri, R. 1998, A&A 333, 864
Georgelin, Y.M., Georgelin, Y.P. 1976, A&A 49, 57
Georgelin, Y.M., Amram, P., Georgelin, Y.P., *et al.* 1994, A&AS 108, 513
Georgelin, Y.M., Russeil, D., Marcelin, M., *et al.* 1996, A&AS 308, 588
Georgelin, Y.M., Russeil, D., Amram, P., *et al.* 2000, A&A 357, 308
Grabelsky, D.A., Cohen, R.S., Bronfman, L., Thaddeus, P. 1988, ApJ 331, 181

Gunn, J.E., Knapp, G.R., Tremaine, S.D. 1979, AJ 84, 1181
Heyer, M.H., Terebey, S. 1998, ApJ 502, 265
Hodge, P.W., Kennicutt, R.C. 1983, AJ 88, 296
Humphreys, R.M. 1970, AJ 75, 602
Humphreys, R.M. 1972, A&A 20, 29
Humphreys, R.M. 1976, PASP 88, 647
Jacq, T., Despois, D., Baudry, A. 1988, A&A 195, 93
Kaltcheva, N.T., Hilditch, R.W. 2000, MNRAS 312, 753
Kennicutt, R.C. 1981, AJ 86, 1847
le Coarer, E., Amram, P., Boulesteix, J., *et al.* 1992, A&A 257, 389
Loinard, L., Dame, T.M., Heyer, M.M., Lequeux, J., Thaddeus, P. 1999, A&A 351, 1087
Mel'nik, A.M., Efremov, Y.N. 1995, Astrophys. Letters 21, 10
Merrifield, M.R. 1992, AJ 103, 1552
Mezger, P.G. 1970, in: W. Becker & G. Contopoulos (eds.), *The Spiral Structure of our Galaxy*, Proc. IAU Symp. No. 38 (Dordrecht: Reidel), p. 107
Morgan, W.W., Sharpless, S., Osterbrock, D. 1952, AJ 57, 3
Morgan, W.W., Whitford, A.E., Code, A.D. 1953, ApJ 118, 318
Olling, R.P., Merrifield, M.R. 1998, MNRAS 297, 943
Reynolds, R.J. 1983, ApJ 268, 698
Rickard, J.J. 1968, ApJ 152, 1019
Rohlfs, K., Chini, R., Wink, J.E., Bohme, R. 1986, A&A 158, 181
Rozas, M., Zurita, A., Beckman, J.E. 2000, A&A 354, 823
Rumstay, K.S., Kaufman, M. 1983, ApJ 274, 611
Russeil, D. 1997, A&A 319, 788
Russeil, D. 2003, A&A 397, 133
Sandage, A. 1961, *The Hubble Atlas of Galaxies* (Washington, D.C.: Carnegie Institution of Washington)
Schmidt-Kaler, T. 1983, *Landolt-Bornstein*, New Series, Group VI Vol. 2B, 14
Sinha, S.P. 1978, A&A 69, 227
Sodroski, T.J. 1991, ApJ 366, 95
Solomon, P.M., Rivolo, A.R. 1989, ApJ 339, 919
Turbide, L., Moffat, A.F.J. 1993, AJ 105, 1831
Turner, D.G. 1980, ApJ 240, 137
Vacca, W.D., Garmany, C.D., Shull, J.M. 1996, ApJ 460, 914
Vogt, N., Moffat, A.F.J. 1975, A&A 39, 477
Walborn, N.R. 1972, AJ 77, 312
Walborn, N.R. 1973, AJ 78, 1067
Zuckerman, B., Palmer, P. 1974, Ann. Review Astron. Astrophys. 12, 279

Discussion

MAÍZ-APELLÁNIZ: Can you use the data from your Hα survey to quantify what fraction of the ISM volume is filled by the DIG?

RUSSEIL: Unfortunately, it is not possible, because the Hα survey is not systematically calibrated in intensity.

HUMPHREYS: You mentioned the problem of internal scatter in the velocities in the star-forming complexes. But in your kinematic distances, do you take into account non-circular motions? Deviations of only 5 - 10 km s^{-1} can introduce errors of 1 kpc in some directions.

RUSSEIL: Yes, we made a systematic search for velocity departures when stellar distance and kinematic distance are available. Then we take into account the identified departures, to establish the kinematic distance of complexes with only kinematic distance determination.

WALBORN: I would add or emphasize the following uncertainties in the distances and absolute magnitude calibration of the O-type stars: (*i*) unresolved multiple systems; (*ii*) reddening laws (may vary from star to star in some H II regions); and (*iii*) association membership: I've recently found several cases in which more distant O-type stars in a similar line of sight have been mistakenly associated with a less distant OB association — an apparent-magnitude limit effect.

RUSSEIL: I agree with your comment.

VAN DER HUCHT: Why is it that in the 1st and 4th quadrant of your distribution excitation parameters (determining the size of the H II regions in your plot) are on average larger than in the other two quadrants?

RUSSEIL: A part of this effect can be attributed to the fact that, close to the Sun, the spatial extent on projection onto the plane of the sky of complex can bias the grouping, in the sense that we see more details. Another effect can be due to the fact that in the 2nd and 3rd quadrant, one probes the more external part of the Galaxy where complex's luminosity can be fainter.

CONTI: I'd like to congratulate you on this beautifully presented and thorough investigation. My question concerns uncertainty in the distance from the rotation model. You now have some objects with 'stellar' and with 'radio' distances. What is the size of the difference? Systematic by quadrant?

RUSSEIL: In fact, we compare rotational velocities deduced from radial velocity measurements and from stellar distance, which is the same approach as to compare the distance. This allows us to put in evidence circular rotation departures which vary from arm to arm: the Perseus arm shows a quite large velocity departure ($\sim$21 km s^{-1}), while the Sagittarius-Carina arm exhibits small velocity departures ($\sim$3 km s^{-1}).