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SOME NEW RESEARCH ON THE MAGELLANIC CLOUDS

James Lequeux
Observatoire de Meudon, 92195 Meudon CEDEX, France, and Ecole Normale Superieure

RESUMEN

Se presenta una revisiónn de investigaciones recientes selectas de las Nubes de Magallanes en relación a los siguientes temas: estructura, materia interestelar y en particular nubes moleculares y polvo, y algunos temas selectos de poblaciones y evolución estelares. Se hace énfasis en algunos puntos dignos de mayor estudio.

ABSTRACT

This review summarizes selected recent research on the Magellanic Clouds concentrating on the following topics: structure, interstellar matter and in particular molecular clouds and dust, selected items on stellar populations and evolution. Some points worthy of further studies are emphasized.

Key words: **MAGELLANIC CLOUDS**

1. INTRODUCTION

In this review I wish to summarize some recent research on the Magellanic Clouds, selected according to my own taste thus strongly biased towards a few topics. I will first discuss a few points connected with the structure of the Magellanic Clouds, then emphasize some recent work on the interstellar matter in the Clouds, say a few things about stellar populations and finally make a few remarks on the problem of the evolution of the Magellanic Clouds. This review will of course bear heavily upon some recent publications: amongst other the proceedings of the IAU Symposium 148 in Sydney (Haynes & Milne 1991), those of the meeting in Heidelberg "New aspects of Magellanic Cloud Research" (Baschek et al. 1993), and the excellent reviews by Westerlund (1990) and (on Magellanic Cloud clusters) by van den Bergh (1991).

2. THE STRUCTURE OF THE MAGELLANIC CLOUDS

2.1. The Small Magellanic Cloud

The structure, and in particular the extent in depth of the Small Magellanic Cloud (SMC) has been and still is the subject of controversies. The reasons are i) the complicated structure of the gas in the SMC (2 to 4 components according to the authors); ii) the difficulties in relating the stars to the gas and iii) the difficulties in obtaining sufficiently accurate distances for the stars (this is of course hopeless for the gas). Let us examine these points in turn.

There are at present extensive observations of the whole SMC in the 21-cm line of atomic hydrogen made with the Parkes radiotelescope but their interpretation in terms of gas structure is difficult. Mathewson & Ford (1984), using a single position-velocity cut along the main body (the "bar") of the SMC, find two components about equal, each of them rotating, while a 3-dimension analysis by Martin et al. (1989) yields two main components and two secondary ones with different velocities, all non-rotating. The difference comes from the way of connecting the velocities of the 21-cm profiles at adjacent positions. Note that Torres & Carranza (1987) were the first to find four components with different radial velocities using a variety of tracers.

As no direct determination of the distance of gas is possible, the next step in determining the 3-dimensional structure of the SMC is to find stars spatially associated with the gas and to measure their distance. It only makes sense to associate young stars with the gas, as older stars may have lost memory of their birthplaces.

Martin et al. (1989) have studied the association of gas with young stars having accurate radial velocities, mainly red supergiants. They find that while most young stars are clearly associated with the gas, a fraction are not as there is no gas at their radial velocity in their direction: probably the gas has been expelled by supernova explosions, stellar winds or expansion of HII regions. Keeping only the associated stars, it has been possible to show from a study of the radial velocity of the interstellar absorption lines in the spectrum of stars belonging to the various gas components that the main component with the lower velocity is located in front of the other main component (Martin et al. 1989 and references herein).

Determining the distance of the different components, or at least the extent in depth of the SMC, is the last step in the process. Martin et al. (1989) find no significant difference between the mean apparent magnitudes of similar stars belonging to the four substructures of the SMC, and conclude that the depth of the SMC is not larger than about 10 kpc. Conversely Mathewson et al. (1988) find a larger distance spread (about 15 kpc) for the cepheids they have studied, using the period/luminosity relation. However there seems to exist a scatter in the absolute magnitudes of cepheids of a given period (Welch et al. 1987), they have only a few photometric measurements per cepheid and their mean apparent magnitudes are not very accurate. Mathewson et al. (1988) also determine mean radial velocities for their cepheids but they are not accurate either because velocities have been measured only at a few phases in the pulsation. Thus attempts to associate cepheids to the various HI components are not yet convincing: see Lequeux (1991) for a more complete discussion. I consider the problem of the depth of the SMC as still unsettled. It is clear however that the answer will ultimately come from very well observed cepheids.

2.2. The Large Magellanic Cloud

At first glance, the situation looks simpler for the Large Magellanic Cloud (LMC): the LMC is basically an inclined, rotating disk, but...

i) The 21-cm line profiles are double over most of the LMC. Thus the very determination of the rotation curve of the LMC is not without problems. A comparison of the velocities of the two HI peaks with those of the red supergiants in the same direction gives various results (Prevot et al. 1989) and does not allow to see clearly which of the HI components is more representative of the disk. We do not really know the origin of the double HI profiles, the distance between the components, etc. although some brave attempts have been made e.g. by Luks & Rohlfs (1992).

ii) The velocity field of the LMC looks skewed. This appears to be due to a large extent to a transverse motion (proper motion) of the LMC, as convincingly shown by Prevot et al. (1989) and by Luks & Rohlfs (1992): due to the large angular extent of the LMC, the longitudinal component corresponding to this transverse motion is far from negligible at large angular distances from the center and varies of course with the position angle of the considered point. Assuming that the distorsions in the velocity field are essentially due to the transverse motion of the LMC it is indeed possible to infer its transverse velocity (about 150 km/s towards p.a. 110 degrees according to Prevot et al. 1989). It is remarkable that this value is close to that predicted from the orientation of the Magellanic stream if the origin of the stream is ram- pressure stripping. Several astrometric programs for determining directly the corresponding proper motion are under way, in particular with the HIPPARCOS satellite.

iii) A recent study of the polarization and Faraday rotation of the continuum radio emission suggests that a magnetic structure (loop?) is protruding from the disk of the LMC in the region of 30 Dor (Klein et al. 1992).

iv) Interstellar line profiles in the direction of LMC (and SMC) stars show multiple components often at velocities different from those of the HI line in the same direction. The best-known example is of course in the direction of SN 1987A (Vidal-Madjar et al. 1987; de Boer et al. 1987; Vladilo et al. 1993). The origin of the corresponding gas, some of which could be in the galactic halo or at intermediate distances, is not well understood. It is remarkable that in general the "anomalous" interstellar line components are strong in CaII and weak in NaI, like in the galactic "high-velocity clouds" of Spitzer and Routly: this may indicate fast-moving material in which the dust grains have been partly destroyed by sputtering, liberating calcium.

2.3. The Bridge between the Clouds and the Magellanic Stream

These features have been first discovered in the 21-cm line and are obvious results of mutual interactions between the Clouds and also between them and the Galaxy. The corresponding HI maps can be found in Mathewson & Ford (1984). The bridge between the Clouds is now known to contain young stars and associations with ages of about 100 million years, the same as for objects in the tip of the wing of the LMC and in the southern arc of the LMC (Irwin et al. 1985; Irwin 1991 and references herein; Pierre 1987). Conversely, no stars have been found in the Magellanic stream although it contains a significant quantity of gas. This points to different origins: the bridge and the other mentioned features might be of tidal origin, or at least have experienced a perturbation of tidal origin that triggered star formation 100 million years ago. The stream is more likely due to some hydrodynamical process like ram-pressure stripping. It contains heavy elements but in unknown quantities (Songaila 1981). IRAS has not detected the far-IR emission of those features. However given the relatively low radiation field which can heat the dust this non-detection is not incompatible with a normal (LMC or even galactic) abundance of dust. Determinations of the abundance of dust, which should give a hint about the general abundances then the origin of the bridge and the stream, will have to await the launch of the Infrared Space Observatory (ISO) in 1994.

3. INTERSTELLAR MATTER IN THE MAGELLANIC CLOUDS

The Magellanic Clouds contain large quantities of interstellar matter (ISM): about 10% of the total mass for the LMC and 30% for the SMC. Considerable progress has been made recently in observations of the ISM, although the corresponding interpretation is still in an early stage. New surveys have been performed not only in HI with the Parkes radiotelescope but also as follows: - Far-IR with IRAS (Schwering 1988); following experience gained in the reduction of IRAS data, better and better maps are constantly being obtained; - millimeter-lines of the CO molecule: see later; - H alpha: the Marseille-ESO survey: see Rosado, this Conference, and Le Coarer (1992); - [CII] 158 micrometers, with the Kuiper Airborne Laboratory: Israel (1993); - X-rays: EINSTEIN data (Wang et al. 1991), and unpublished ROSAT data.

I will now concentrate on the molecular gas and on dust

3.1. Molecular gas in the Magellanic Clouds

Complete low-resolution surveys of both Clouds have been performed with the Columbia/CfA 1.2 m Millimeter Wave Telescope at CTIO in the (1-0) line of CO at 115 GHz (Cohen et al. 1988; Rubio et al. 1990). These surveys have detected CO in many regions of both Clouds, albeit with lower intensities than in the Galaxy. From the extent of the CO complexes and the width of the CO line which is due to velocity dispersion, they found virial masses similar to those of the Galactic molecular complexes of the same size (a few hundred of parsecs). Assuming that this mass is under the form of molecular hydrogen, they derived conversion factors between the CO line intensity and the column density of molecular hydrogen considerably larger that the Galactic factor, by about 6 times for the LMC and 20 times for the SMC. Still the total mass of molecular hydrogen derived in this way is only 30 % of that of atomic hydrogen in the LMC and 7 % in the SMC instead of 50 % for the Galaxy.

New, higher resolution observations of the CO(1-0) line and of other lines of CO and of its isotopic substitutions made with the Swedish-ESO Submillimeter Telescope (SEST) at La Silla have considerably improved this picture: for the SMC see Israel et al. (1993), Rubio et al. (1993a, 1993b) and Rubio (this Conference); preliminary results for the LMC can be found in Johansson (1991) and Israel & de Graauw (1991). At least for the SMC it appears that the CO emission comes from relatively small clouds (10-20 pc in radius) and that there is no CO emission from the more diffuse ISM, contrary to what occurs in the Galaxy. Even for these small clouds CO occupies only a fraction of the volume and is relatively hot. This can be understood as the effect of photodissociation which is more important in the SMC than in the Galaxy due to a higher surface density of young, hot stars and a lower abundance of dust and molecules. The ratio (CO line absolute intensity)/(virial mass) is not very different for the small clouds in the SMC and in the Galaxy, contrary to the situation at larger scales described above. It is likely that due to photodissociation there is not only very little CO, but also very little molecular hydrogen outside the small clouds: thus the virial mass determined at large scales is presumably mostly in atomic hydrogen rather than molecular hydrogen; even in the small clouds, it is possible that a large fraction of the gas is atomic rather than molecular: thus the fractions of molecular hydrogen determined on the basis of the low-resolution CO observations are only strong upper limits. New, high resolution 21-cm observations with the Australia Telescope (Parkes radiotelescope and compact array) are under way to check those ideas. It is interesting to note that the new H-alpha Marseille-ESO survey of the SMC mentioned above has detected diffuse ionized gas everywhere in the Cloud, another indication that the diffuse ISM is bathed in a strong far- UV radiation field. The few existing [CII] far-IR line observations (Israel 1993) also confirm the general picture.

The morphological relation between the CO clouds and other tracers of the gas and young stars has not been much studied yet. The CO clouds often coincide with optical absorption patches and are often, but not always associated with HII regions as in our Galaxy. An interesting example is offered by the region of N11 in the LMC. Comparing the CO map (see fig. 1 of Israel & de Graauw 1991) with the optical picture recently published by Walborn & Parker (1992), one sees the following: i) most CO clouds are on a circle surrounding a giant bubble dug in the ISM by the stars of the central first-generation stellar association: they are potential sites for further star formation; ii) indeed a few CO clouds are clearly associated with the second-generation very young stellar associations + HII regions N11A and N11B; iii) a tail of CO clouds to the NE is not obviously associated with young stars and HII regions: its significance for star formation has to be elucidated. It is exceptional that the relations between CO clouds and star formation are evidenced to such a degree of visibility. This illustrates the high interest of CO observations in the Magellanic Clouds.

3.2. Interstellar dust in the Magellanic Clouds

As for molecular gas, the properties of interstellar dust are different in the Magellanic Clouds and in the Galaxy. It has been known for some time that the far-UV extinction curves differ in the three cases and that the dust-to-gas ratios follow roughly the heavy-element abundances (Bouchet et al. 1985). Far- IR studies based on IRAS observations also show different properties (Sauvage et al. 1990). First, the 60/100 micrometers intensity ratio is larger than in the Galaxy. To the extent that this ratio can be interpreted in terms of temperature of relatively large ("normal") dust grains, this property can be understood as resulting from the higher average far-UV radiation field in the Clouds. Another property is the weakness of the emission at 12 micrometers. In the Galaxy, this emission is generally attributed to very small grains, perhaps polycyclic aromatic hydrocarbons (PAHs): Desert et al. (1990). Is its deficiency in the Clouds related to a lack of such particles, itself due to a (controversial) lower abundance of carbon relative to oxygen? Is this related to the "anomalies" in the far-UV extinction curves of the Clouds? No answer has been possible for the moment, but much is expected from observations with ISO.

4. STELLAR POPULATIONS IN THE MAGELLANIC CLOUDS

4.1. Study of stellar evolution using the Magellanic Clouds

The Magellanic Clouds are ideal places to study stellar populations as there is little problem with the distance of the stars compared to our Galaxy. In particular, the study of evolved stars has gained enormously from observations in the Clouds as their absolute magnitudes are notoriously difficult to obtain in our Galaxy from photometry and spectroscopy (a good very recent example of a Magellanic Cloud study is that of the OH/IR stars by Wood et al. 1992). Due to this, the Magellanic Clouds are excellent test benchs for stellar evolution. They have revealed a number of surprises, amongst which: i) the upper HR diagram shows an unexpectedly large number of stars at the left of the conventional main-sequence (see e.g. Fitzpatrick & Garmany 1990). This has an obvious bearing on the way stars evolve at high masses, which is still rather uncertain; ii) a large fraction of the supergiants are enriched in nitrogen (see e.g. Bohannan & Fitzpatrick 1993), much more for example than predicted by Maeder & Meynet (1987); as the previous fact, this points towards very important blue loops in the HR diagram evolution. Recent evolution models (Schaerer et al. 1993) attempt to reproduce these properties, but is is probable that the last word is far from having been said. Note in the same vein that the final evolution of the progenitor of SN 1987A, a 20 solar mass blue star enriched in nitrogen, is still very controversial in spite of much effort.

4.2. Stellar populations, star formation and evolution of the Magellanic Clouds

Another series of problems whose solution this time uses an a-priori knowledge of stellar evolution concerns the star formation and its evolution in the Magellanic Clouds. This is a very broad topic which would deserve a full review by itself; only a few words will be said here.

First, the Magellanic Clouds are excellent test benchs for studying star formation, in particular for massive stars that can be easily observed. I have mentioned previously the case of the N11 region in the LMC. It bears similarities with the 30 Doradus region in which contagious star formation is also at work. In the latter case, still-embedded newly-born stars have been revealed by near-IR imaging in molecular clouds shocked by a bubble originating in the central star cluster (Rubio et al. 1992). This central cluster and others can be considered as the youngest of the "globular" clusters found in the Magellanic Clouds and some other galaxies like M 33, but not in our Galaxy for reasons not well understood. It has also been possible to see that most, and perhaps all of the brightest "stars" in the Magellanic Clouds actually are not single objects, but multiple systems: see e.g. Heydari-Malayeri & Hutsemekers (1991). No bona fide star more massive than 80-100 solar mass has ever been seen anywhere -in particular in the Magellanic Clouds-; this has profund implications on the mechanisms of star formation. However, the composite nature of the brightest stars in galaxies does not seem to affect their use as standard candles for cosmology (see Tikhonov & Karachentsev 1993), an interesting fact in itself since it shows that the luminosity of the brightest young multiple systems is similar in different galaxies.

Turning now to old stars, it is clear that they have a different space distribution and even kinematics than the young objects. This is obvious for many categories of objects: old "halo" stars (Gardiner & Hatzidimitriou 1992), clusters (van den Bergh 1991; Schommer 1991), CH stars (Cowley & Hartwick 1991); for intermediate-age population in the SMC like carbon stars see Azzopardi & Rebeirot (1991). The rather regular distribution of old and intermediate-age objects, which contrasts very much with the distribution of young objects especially in the case of the SMC, may be a remnant from ancient times where little or no interaction existed between the Clouds and the Galaxy.

5. CHEMICAL COMPOSITION AND EVOLUTION OF THE MAGELLANIC CLOUDS

In spite of being a rather ancient topic, it is still a very controversial one. Let me state first a few (relative!) certainties: i) The colors indicate a globally uniform average star formation rate (SFR) in the past in the case of the LMC and a somewhat decreasing one for the SMC (see e.g. Rocca-Volmerange et al. 1981); note that the colors do NOT allow to study the fluctuations of the SFR in time, e.g. bursts of SF, as shown many years ago by Larson & Tinsley (1978); ii) the fraction of residual gas and the overall abundances confirm the different evolutionary stages of the Galaxy, the LMC and the SMC; iii) the smoothly decreasing SFR of the SMC is confirmed by the age- metallicity relation for its clusters (da Costa 1991). Conversely, in the LMC, while there is also an indication of a decreasing age-metallicity relation there are very few stars and clusters at ages larger than 4 billion years and smaller than about 10 billion years. This indicates a rather irregular variation of the SFR with time, probably due to interactions with the SMC and the Galaxy.

Most of the rest is controversial. Here are a few points certainly worth further study: i) if the metallicity Z obeys the simple closed-box evolution law (Larson & Tinsley 1978) $Z = y \ln(Mtot/Mgas)$ where Mtot and Mgas are the total mass and the mass of gas respectively, the yield y in heavy elements is about 3 times smaller than predicted by the current models of nucleosynthesis; this property is true not only for the Magellanic Clouds, but for most irregular galaxies, and has bee known for a long time (see e.g. Lequeux et al. 1979); a possible way out of this difficulty is to decrease the yield by assuming that the stars more massive than 20-25 solar masses never become supernovae (Maeder 1992); ii) determinations of the abundances of various elements in different classes of young objects in the Magellanic Clouds (hot and cold supergiants, HII regions, etc.) often give discrepant results; it is hard to understand such differences if real, but they might be artefacts due to systematic effects in the different methods of abundance determinations for these different objects (Pagel 1993); the case of carbon, a key element in many respects (see the previous discussion on interstellar dust), is of particular concern: further efforts are necessary to clear up the situation; in the mean time, it is better to refrain from speculating too much on the chemical evolution of the Magellanic Clouds.

REFERENCES

Azzopardi M., Rebeirot E., 1991, in Haynes & Milne (1991), p. 71
Baschek B., Klare G., Lequeux J., eds., 1993, New aspects of Magellanic Cloud research, Springer-Verlag, Berlin, in press
Bohannan B., Fitzpatrick E.L., 1993, in Baschek et al. (1993)
Bouchet P., Lequeux J., Maurice E., Prevot L., Prevot-Burnichon M.-L., 1985, A&A 149, 330
Cohen R.S., Dame T.M., Garay G., Montani J., Rubio M., Thaddeus P., 1988, ApJ 331, L95
Cowley A.P., Hartwick F.D.A., 1991, ApJ 373, 80
da Costa G.S., 1991, in Haynes & Milne (1991), p. 183
de Boer K.S., Grewing M., Richtler T., Wamsteker W., Gry C., Panagia N., 1987, A&A 177, L37
Desert F.-X., Boulanger F., Puget J.-L., 1990, A&A 237, 215
Fitzpatrick E.L., Garmany C.D., 1990, ApJ 363, 119
Gardiner L.T., Hatzidimitriou, D., 1992, MNRAS 257, 195
Haynes R., Milne D., eds., 1991, The Magellanic Clouds, IAU Symposium No. 148, Kluwer, Dordrecht
Heydari-Malayeri M., Hutsemekers D., 1991, A&A 243, 401

Irwin M.J., 1991, in Haynes & Milne (1991), p. 453
Irwin M.J., Kunkel W.E., Demers S., 1985, Nature 318, 160
Israel F.P., 1993, in Baschek et al. (1993)
Israel F.P., de Graauw Th., 1991, in Haynes & Milne (1991) p. 45
Israel F.P., Johansson L.E.B., Lequeux J., Booth R.S., Nyman L.-A., Crane P., Rubio M., de Graauw Th., Kutner M.L., Gredel R., Boulanger F., Garay G., Westerlund B., 1993, A&A in press
Johansson L.E.B. 1991 in Dynamics of Galaxies and their molecular cloud distributions, Casoli F. & Combes F., eds., Kluwer, Dordrecht, p. 1
Klein U., Haynes R.F., Wielebinski R., Meinert D., 1993, A&A, submitted
Larson R.B., Tinsley B.M., 1978, ApJ 219, 46
Le Coarer E., 1992, Thesis, University of Marseille-I; also in Baschek et al. (1993)
Lequeux J., 1991, in Haynes & Milne (1991), p. 25
Lequeux J., Peimbert M., Rayo, J.F., Serrano, A., Torres-Peimbert S., 1979, A&A 80, 155
Luks T., Rohlfs K., 1992, A&A 263, 41
Maeder A., 1992, A&A 264, 105
Maeder A., Meynet G., 1987, A&A 182, 243
Martin N., Maurice E., Lequeux J., 1989, A&A 215, 219
Mathewson D.S., Ford V.L., Visvanathan N., 1988, ApJ 333, 617
Pagel, B.E.J., 1993, in Baschek et al. (1993)
Pierre M., 1987, A&A 175, 54
Prevot L., Rousseau J., Martin N., 1989, A&A 225, 303
Rocca-Volmerange B., Lequeux J., Maucherat-Joubert M., 1981, A&A 104, 177
Rubio M., Garay G., Montani J., Thaddeus P., 1991, ApJ 368, 173
Rubio M., Lequeux J., Boulanger F., Booth R.S., Garay G., de Graauw Th., Israel F.P., Johansson L.E.B., Kutner M.L., Nyman L.-A., 1993a, A&A in press
Rubio M., Lequeux J., Boulanger F., 1993b, A&A in press
Rubio M., Roth M., Garcia J., 1992, A&A 261, L29
Sauvage M., Thuan T.X., Vigroux L., 1990, A&A 237, 296
Schaerer D., Meynet G., Maeder A., Schaller G., 1993, A&AS in press
Schommer R.A., 1991, in Haynes & Milne (1991), p. 171
Songaila A., 1981, ApJ 243, L19
Schwering P.B.W., 1988, PhD Thesis, Leiden University
Tikhonov N.A., Karachentsev I.D., 1993, A&A in press
Torres G., Carranza G.J., 1987, MNRAS 226, 513
van den Bergh, S., 1991, ApJ 369, 1
Vidal-Madjar A., Andreani P., Cristiani S., Ferlet R., Lanz T., Vladilo G., 1987, A&A 177, L17
Vladilo G., Molaro P., Monai S., d'Odorico S., Ferlet R., Vidal-Madjar A., 1993, A&A in press
Walborn N.R., Parker J.Wm., 1992, ApJ 399, L87
Wang Q., Hamilton T., Helfand D.J., Wu X., 1991, ApJ 374, 475
Welch D.L., McLaren R.A., Madore B.F., McAlary C.W., 1987, ApJ 231, 162
Westerlund B.E., 1990, A&A Review 2, 29
Wood P.R., Whiteoak J.B., Hugues S.M.G., Bessell M.S., Gardner F.F., Hyland A.R., 1992, ApJ 397, 552

James Lequeux, Observatoire de Meudon, 92195 Meudon CEDEX, France, and Ecole Normale Superieure