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## STAR FORMATION IN THE MAGELLANIC CLOUDS

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**ABSTRACT.** Because of their proximity, the Magellanic Clouds provide us with the opportunity to conduct a detailed study of the history and current state of star formation in dwarf irregular galaxies. There is considerable evidence that star formation in the Clouds has been and is proceeding in a manner different from that found in a typical well-ordered spiral galaxy. Star formation in both Clouds appears to have undergone a number of relatively intense bursts. There exist a number of similarities and differences in the current state of star formation in the Magellanic Clouds and the Milky Way. Examination of IRAS sources with ground based telescopes allows identification of highly evolved massive stars with circumstellar shells as well as several types of compact emission line objects.

## 1. A BRIEF OVERVIEW OF STAR FORMATION IN THE CLOUDS

We are all familiar with the well-worn cliché concerning the inability to see forests because of the trees. In astronomy the converse is often true: while global properties of galaxies can easily be studied, the extent to which the individual constituents can be observed is severely limited. But it is these individual constituents - stars and clouds of gas - that determine the appearance and evolution of a galaxy. The Magellanic Clouds present us with a unique opportunity to study the stellar content of two galaxies in considerable detail and to provide some insight to the problems of star formation and evolution in a galaxy-wide context. In this first section I will briefly review some ideas of the history of star formation in the Magellanic Clouds.

## 1.1 Old Stars

There is a population of stars in both Clouds which is the equivalent of the halo population of the Milky Way. These stars are old,  $\geq 10^{10}$  yr, and metal poor. The two most obvious examples of this stellar population are RR Lyrae variables, found throughout both Clouds, and star clusters similar to metal poor globular clusters in the Milky Way. These stars have a metallicity between 30 and 100 times less than solar. The SMC's old population is more metal poor than the LMC's. These old stars constitute about 6% by mass of both Clouds, the same as that for the Galaxy's halo population interior to the solar circle (Frogel 1984).

## 1.2 Intermediate Age Stars

About 5 Gyr ago there appears to have been a major burst of star forming activity in the Clouds. Strong evidence for this comes from optical color-magnitude diagrams and luminosity functions constructed for a number of fields in both Clouds (*e.g.* Butcher 1977; Stryker 1984); from the discovery of large numbers of luminous asymptotic giant branch (AGB) M and C stars located throughout both Clouds (Blanco, McCarthy, and Blanco 1980); and, finally, from the relative number of clusters of intermediate age (*e.g.* Bica, Dottori, and Pastoriza 1986), although this line of argument has been questioned by Elson and Fall (1985).

As is the case for the oldest stars, the intermediate age population in the LMC has a higher mean metallicity than that of the SMC. On the whole, metal enrichment of the interstellar medium in the LMC appears to have occurred at a higher rate over time than that in the SMC. But even in the LMC, enrichment has proceeded much more slowly than in the Milky Way (*e.g.* Twarog 1980). References to discussions of these topics may be found in a more lengthy review article (Frogel 1984).

## 1.3 Young Stars

There is a significant population of objects in the Magellanic Clouds with an age of order  $10^8$  yrs. It is best typified by the so-called blue globular clusters and the Cepheid variables. Morphologically, the blue globulars resemble Galactic globular clusters. However, their turn-off mass is about 5-7  $M_{\odot}$  and their metallicity is only a factor of two down from solar. They have no obvious Galactic counterparts and appear to have formed in regions of very low gas density (Freeman 1980). The conditions which brought about their formation seem to be quite different from those which occur in the Galactic disk.

The blue globulars and AGB stars of similar age in the field of the Magellanic Clouds appear to be the result of an enhanced epoch of star formation with a production about 10% of that in the intermediate age stellar component (Frogel and Blanco 1983).

## 2. CURRENT STAR FORMATION

Scoville pointed out in his review talk this morning that essentially all star formation in our galaxy takes place in giant molecular clouds (GMC) which are delineated by their CO line emission. In the Magellanic Clouds there is clearly a great deal of current star forming activity. For example there are large numbers of OB stars and late type supergiants in the field of both Clouds as well as many young stellar associations and HII regions. However, the preliminary evidence from the Columbia CO survey of both the LMC and SMC pointed to a low molecular abundance.

Results of a CO survey of the LMC reported by Cohen, *et al.* (1984) indicated that  $H_2/HII$  is 5-10 times lower than in the Milky Way. A similar survey of the SMC by Rubio, *et al.* indicated an even lower ratio there. These results of course depend critically on the assumption that the CO to  $H_2$  ratio is the same as in the Galaxy. With the possible exception

of the N159 region in the LMC, Israel (1984) found no unambiguous evidence on the basis of CO line strengths for GMC complexes in the Clouds as exist in the Milky Way.

More recently, Israel, *et al.* (1986) have argued that the CO abundance of both clouds is low not just, or even primarily, because of the low overall abundance of heavy elements, but because of the high destruction rate of molecules due to the strong interstellar UV radiation field and lower gas-to-dust ratios; the latter results in less shielding of the CO molecules. Hence, use of a Galactic H<sub>2</sub>/CO ratio will result in gross underestimation of the H<sub>2</sub> abundance since this molecule is much less affected by the interstellar UV field than CO. Their model also qualitatively accounts for the relative CO strengths between the Large and Small Cloud. A search for H<sub>2</sub> from HII regions in the Clouds has in fact revealed its presence in quite a few objects (Israel 1986). Its discovery supports Israel, *et al.*'s contention that its true abundance cannot be inferred from observations of CO.

As reported in the poster paper at this conference by Jones, Hyland, and Harvey (hereafter PI) there appears to be a lack of high surface brightness, compact infrared cores to HII regions in the Clouds as are found in many Galactic HII regions where star formation is taking place. Elias and Frogel, in another poster paper (hereafter PII), note that they have been able to identify only a few IRAS sources associated with HII regions that are compact. "Compact" here means that the IRAS 12 and 25 $\mu$ m fluxes are only slightly greater than equivalent fluxes measured from the ground in apertures of a few arcseconds in diameter. In any case, the point is that such objects are rare in the Clouds. Most IRAS sources associated with HII regions are quite extended (PII). There also is an absence of highly obscured but IR/radio luminous HII regions in the Clouds (PI).

Gatley, *et al.* (1981, 1982) have found obscured compact objects in the SMC and LMC which they identify as protostars but Jones, *et al.* (1986 and PI) note a general absence of low luminosity protostellar objects. Also, they find an apparent under luminosity of the HII regions for the number of ionizing photons that are inferred when compared with Galactic HII regions and the IMF of stars therein. Their interpretation of this result is that the cause is a lack of intermediate mass stars in regions of star formation. This conclusion is quite dependent on the assumption that all of the light from OB stars in the HII region is absorbed by dust and subsequently reradiated in the infrared. On the other hand, Hunter, *et al.* (1986) find that  $L(\text{IR}/\text{H}\alpha)$  is about the same for all dwarf galaxies with IRAS data and that this ratio is "roughly consistent with both luminosities measuring the integrated OB stellar luminosity output."

There is, of course, a danger in trying to derive an IMF from a sample of stars that represents an extremely limited slice of space and time. While there may well be some differences within HII regions, globally the IMFs for the LMC and the solar neighborhood appear to be quite similar, even for the massive stars (Humphreys and McElroy 1984).

Elias and Frogel (PII) have been attempting to identify and obtain near infrared and optical spectroscopy of IRAS sources in the Magellanic Clouds. They have observed about 65 sources, two-thirds of which have IRAS colors typical of stars. Two general results of this survey are: 1) The

relative scarcity of compact infrared sources in association with HII regions (discussed above); and, 2) a generally lower level of star forming activity in the SMC relative to the LMC.

The IRAS data by themselves cannot distinguish between luminous stars in the Magellanic Clouds and nearby field stars. Near infrared data, though, divides the IRAS sources up into three reasonably well separated categories. The first of these, about half of the star-like sources found, have *JHK* colors, CO, and H<sub>2</sub>O indices quite similar to those of late-type giants in the solar neighborhood. Most of these can be identified with visually bright stars. Their *K* magnitudes are brighter than seventh; with very few exceptions no LMC or SMC supergiants are this bright (Elias, Frogel, and Humphreys 1985).

A second category of stellar sources consists of objects with colors and indices typical of late-type giants with circumstellar shells. CCD spectroscopy of the ones with optical counterparts usually reveals exceptionally strong TiO bands. At least one of these, in the SMC, is a carbon star. A few of the sources in this second category have no optical counterparts and probably are extreme examples of dust-enshrouded evolved objects. None, however, are as red or as luminous as the two LMC supergiants found by Elias, Frogel, and Schwope (1986) in their first look at Magellanic Cloud IRAS sources. One of these two has recently been identified as the first OH/IR star in the Magellanic Clouds by Wood, Bessell, and Whiteoak (1986). It should be remembered that although these cool, luminous stars are highly evolved, they are quite young and as such can yield important information on current star formation in the Magellanic Clouds. In particular they must play an important role in the enrichment and recycling of interstellar material.

The third category into which Magellanic Cloud IRAS sources can be divided on the basis of ground based data is compact or stellar emission line objects. Some of these are in HII regions. Others appear to be emission line stars. Some have optical spectra - permitted emission lines from neutral atomic species and from the calcium triplet - characteristic of pre-main sequence objects surrounded by a relatively dense cloud of gas and dust, presumably the remnant out of which they formed (*cf.* McGregor, Persson, and Cohen 1984). An advantage of studying such objects in the Clouds is the fact that they are all at the same distance so that the accuracy of a derived luminosity function will be limited only by the ability to find them.

In summary, we see that the history of star formation in the Magellanic Clouds and its current status, various aspects of which are considered in some of the poster papers presented at this conference, differ in a number of significant features from the situation in the Milky Way. Globally, star formation in the Clouds would be expected to be different from that in the Galaxy because of their smaller mass and lack of ordered spiral structure. The increasingly well-documented low metallicity of the Clouds, particularly of the SMC, appears to have resulted from a significantly lower rate of enrichment of the interstellar medium in these irregular systems than in the Milky Way. A lower enrichment rate could come about, for example, because of the inability of a low mass galaxy to retain the metal-enriched material present in supernova-driven winds. As pointed out by Vader (1986), such winds, even with a moderate total mass

loss rate, can carry away a substantial fraction of the heavy metal production resulting in a substantially reduced yield. A low present day abundance of heavy metals can be expected to have important effects on current star formation.

The Magellanic Clouds present us with the opportunity to study in great detail star formation in an environment different from that which obtains in the Galactic disk. Let us proceed to examine the trees and the leaves that grow on them so we may be better able to comprehend and appreciate the beauty and complexity of the forest as a whole.

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## DISCUSSION

GALLAGHER:

Can you say anything about the number of OH/IR stars with regard to the death of AGB stars via 'superwinds'?

FROGEL:

Not at this time because our sample is restricted to the outer region of the Clouds where source confusion would not be a problem.

ISRAEL:

Under the extreme conditions exemplified by the Magellanic Clouds (e.g., low heavy-element abundances, relatively strong UV radiation field) one cannot expect CO to be a reliable tracer of H<sub>2</sub>. In fact, despite the weakness of CO, there are several indications that the clouds may contain significant amounts of H<sub>2</sub>. The most indirect indication is that several dark cloud silhouettes can be seen in both clouds with dimensions similar to those of Galactic GMCs.

The second indication is found in the IRAS maps, where several warm, high dust column density sources can be seen that do not have clear HI counterparts. Unless one is willing to accept wildly fluctuating and at times very high dust-to-gas ratios (in a low-z environment!) the obvious explanation is that these sources contain mostly molecular gas.

Third, Koormeef and I have detected several sources of 2 $\mu$ m H<sub>2</sub> emission, in fact in a large fraction of all sources looked at. Although it is very difficult to derive physical parameters such as mass, etc., from these detections, the frequent occurrence of H<sub>2</sub> emission (often at positions where CO is weak or absent) indicates that H<sub>2</sub> may be widespread in both Magellanic Clouds.

FROGEL:

Great! Finding large amounts of H<sub>2</sub> will help with one of the major problems I noted with regard to star formation in the Clouds.

ROCHE:

Did you not find any carbon stars in the Clouds?

FROGEL:

One SMC object is a C star. Without optical spectra, we cannot tell from the IR data we have whether the blank field SMC and LMC sources are C stars or M stars.