# OPTICAL AND THEORETICAL STUDIES OF GIANT CLOUDS IN SPIRAL GALAXIES

Bruce G. Elmegreen

Astronomy Department, Columbia University

Debra Meloy Elmegreen*

Hale Observatories, Carnegie Institution of Washington,
California Institute of Technology

ABSTRACT

An optical study of four spiral galaxies, combined with radiative transfer models for transmitted and scattered light, has led to a determination of the opacities and masses of numerous dark patches and dust lanes that outline spiral structure. The observed compression factors for the spiral-like dust lanes are in accord with our expectations from the theory of gas flow in spiral density waves. Several low density ($10^2$ $cm^{-3}$) clouds containing $10^6$ to $10^7$ $M_\odot$ were also studied. We discuss these results in terms of recent theoretical models of cloud and star formation in spiral galaxies. The long-term evolution of giant molecular clouds is shown to have important consequences for the positions and ages of star formation sites in spiral arms.

---

From the distribution of H II regions in external spiral galaxies, we may infer that massive star formation is enhanced in spiral arms. This increase may be the result of a heightened probability for triggering star formation in pre-existing clouds as they enter or cross a spiral arm, or it may be due to enhanced cloud formation in the arm, followed by some spiral-independent mechanism for star formation inside these clouds. Both points of view have been extensively investigated theoretically, but observations have been inadequate to choose between the two alternatives. The problem is that there has been no significant detection of giant molecular cloud complexes ($10^5$ $M_\odot$) that are known to be without massive OB stars. If such massive clouds were determined to occur with comparable abundance in both the arm and

---

*Visiting Astronomer, Cerro Tololo Inter-American Observatory and Hale Observatories



*B. H. Andrew (ed.), Interstellar Molecules,* 191–196.

interarm regions (as defined by the underlying red spiral of stars), then the first alternative given above would seem to apply. On the other hand, if galactic surveys showed molecular clouds to be associated with spiral arms, then the results would not be so conclusive, since they might indicate either that the clouds form in the arms, or that out of a uniform distribution of clouds, the spiral arm clouds are the hottest (perhaps due to star formation). Most likely, both of these processes occur to varying degrees in the same galaxy.

New optical observations have been undertaken that eventually may resolve this indeterminancy (D. Elmegreen 1979). The object was to locate dust cloud complexes in nearby and nearly face-on spiral galaxies and to determine the gaseous column densities and masses of these individual clouds, to see if any are similar to giant molecular clouds in our own galaxy. Observations of objects the size of the giant cloud complexes (e.g., 50 to 100 pc) require the high angular resolution that currently is available with optical techniques. UBVRI plates obtained at the 4-m CTIO telescope and the 1.2-m Palomar Schmidt telescope were analyzed with 1" resolution on a scanning microphotometer and calibrated with photoelectric photometry. Seeing during the plate exposures was estimated to be 2", corresponding to linear sizes of 23 pc, 70 pc, 76 pc, and 93 pc in the four program galaxies NGC 7793, M101, M74, and M51, respectively.

Apparent dust opacities for discrete clouds were estimated from the differences in surface brightness between the clouds and the adjacent stellar backgrounds (chosen to be free of H II regions and bright stars). <u>True</u> dust opacities were obtained by comparing the observed brightness differences at five bandpasses with models of emission from idealized galaxies containing dust lanes and discrete clouds. Radiative transfer calculations were developed which included the effects of scattered light (D. Elmegreen 1979). The underlying stellar population in the model was fit to the observed colors of the comparison regions by assuming only that the relative scale heights for different stellar types was the same as for our own galaxy. In this way, the distinction between a low opacity, high-latitude cloud and a high opacity, low-latitude cloud can be determined, even though these two clouds may have the same degree of darkness in any one bandpass. This distinction is possible because the stellar population reddens with increasing height above the plane, so the surface brightness in blue light is a sensitive indicator of the cloud's height; while the surface brightness in red light is a better probe of the cloud's intrinsic absorption, primarily due to selective extinction.

A typical value for the visual extinction through the galaxies in the intercloud (comparison) region was found to be in the range of 0.6-1.0 magnitudes, while dust lanes (whether they were on the inside or outside of prominent spiral arms), in addition to numerous dust patches throughout the galaxies, showed some 3 magnitudes of internal extinction. (Measured apparent visual magnitude differences are only several tenths of a magnitude; the eye deceptively increases the contrast between bright and dark regions on a photographic plate). These results explain the common appearance of dust patches and lanes in external galaxies: the distributed gas is so close to unit optical depth in the visual wavelengths that any slight compression or convergence of the gas will give the clear appearance of a dark patch or lane.

Evidently, dust configurations are a sensitive probe of disturbances in the interstellar medium. For the spiral dust lanes, compression factors of 2 to 3 relative to the ambient medium were typical. The six cases (in two galaxies) of spiral arm branches with large pitch angles all had higher compression factors of around 10. Both of these results, especially the observed enhancements of the compression factor in regions where the pitch angle was large, are in accord with our expectations for gas compression due to spiral density waves. However, the presence of equally compressed dust lanes in both the inner and outer parts of many arms may point to additional effects. In any case, it is clear that most dust lanes cannot be interpreted simply as long chains of giant molecular clouds like those seen in our galaxy, because (a) the measured dust lane opacities correspond to average densities of only 6 to 20 $cm^{-3}$, and (b) the dust lane widths of 100 to 200 pc are much larger than the dimensions of the molecular clouds in our galaxy. It is conceivable, however, that some dust lanes contain denser unresolved molecular cores.

Several high latitude clouds with a few magnitudes of extinction were also found; these appear to be similar to high latitude cloud complexes or the top parts of shells seen in our own galaxy, with dimensions of 100 to 200 pc.

Perhaps one of the most interesting results is that in no case was a large (i.e., resolved) dark cloud seen with an intrinsic visual opacity exceeding 12 magnitudes, although such a cloud, if it existed, would have been obvious even in the R and I plates. The three clouds studied that had this intrinsic extinction all had masses in the range of $10^6$ to $10^7$ $M_\odot$, and their mean gas densities were around 100 $cm^{-3}$. The implication is that denser dark clouds in this mass range were not observed because either they are illuminated by massive star formation and H II regions, or they are much smaller than the seeing limit. This means that giant cloud complexes that extend for about 100 pc and contain more than $10^6$ $M_\odot$ probably initiate star formation before their extinction greatly exceeds some 12 magnitudes.

These results may illustrate some of the aspects of a recent theoretical calculation of self-gravitational cloud formation in spiral density wave shocks (B. Elmegreen 1979). The clouds that are expected to form by large-scale galactic processes are similarly massive H I objects ($10^6$ to $10^7$ $M_\odot$), with large sizes and low mean densities. They should not be identified directly with the observed giant molecular cloud complexes in our own galaxy; they are more like superclouds out of which the smaller molecular clouds ($10^5$ $M_\odot$) will form by condensation and fragmentation.

Probably star formation will begin in a $10^5$ $M_\odot$ fragment at about the same time as molecule formation, because the density thresholds are similar. For the purposes of understanding the details of star and cloud formation in spiral arms, we must consider the long-term consequences of massive star formation in one of the individual molecular clouds (see B. Elmegreen 1979). On a timescale of some $10^7$ years, the cloud will be pushed and partially disrupted by the pressures associated with such star formation (H II regions, supernovae, etc.). The sequential formation of OB subgroups may occur at the same time, but on a smaller scale (e.g., every 2 to 3 million years). Since the total mass that becomes ionized may be only several times $10^4$ $M_\odot$ at this later stage, (as observed in OB associations), and since only $10^3$ to $10^4$ $M_\odot$ of stars will form, a considerable amount of neutral material ($10^5$ $M_\odot$) should remain that simply will be pushed around. If the forces are centralized with respect to the cloud, then a large shell consisting of most of the cloud's original mass may form. Alternatively, if the OB stars are consistently on one side of the cloud (as is often observed to be the case), then the cloud will be pushed as a whole to one side, while a relatively small shell may form toward the other side. In any case, a considerable amount of mass still will be available for re-collection or re-collapse into a second generation molecular cloud complex, and star formation most likely will begin again. The total timescale for this generation-to-generation shuffling will be some 20 to 50 million years, and the cloud's total excursion before star formation resumes may cover 200 to 300 pc. If a spiral density wave passes the cloud before the cloud completely disintegrates by these repetitive bursts of star formation, then the cloud may be shocked by the galaxy into forming new stars (Woodward 1976). On the other hand, if the cloud has had enough time to go through several generations and most of the remaining gas has been converted back into the lower density interstellar medium (e.g., in the outer part of a galaxy), then the gas will be available for the formation of a new cloud complex when the spiral density wave eventually does pass. On the average, a steady-state cloud population could be maintained. Evidently, the details of individual cloud evolution on 30 million year timescales and over regions covering 100 to 300 pc play an important role in generating the observed irregularity in positions and ages of star formation sites inside spiral arms.

## REFERENCES

Elmegreen, B.G. (1979). Astrophys. J., 231, pp. 372-383.
Elmegreen, D.M. (1979). Ph.D. Thesis, Harvard University.
Woodward, P.R. (1976). Astrophys. J., 207, pp. 484-501.

## DISCUSSION FOLLOWING ELMEGREEN

*Goss:* Using the Westerbork Synthesis Radio Telescope at 21 cm we have mapped large HI complexes associated with HII regions in M101. The sizes are $\sim$1 kpc, masses $10^7$-$5\times10^7 M_\odot$, and densities 1-10 $cm^{-3}$. Are these your superclouds that were observed optically?

https://doi.org/10.1017/S0074180900072545 Published online by Cambridge University Press

*Elmegreen:* I would expect that the optical superclouds we observed would indeed be prominent in 21 cm line emission. There are several such clouds, however, so we should compare our maps to see if we detect the same ones.

*Silk:* According to Solomon, molecular clouds fill both arm and inter-arm regions. In order for your mechanism of spiral arm formation and subsequent shuffling to be valid, very long lifetimes for individual molecular clouds are presumably needed. How long a lifetime do you require at a distance of, say, 8 kpc from the center of our galaxy, and how do you think this is achieved?

*Elmegreen:* Individual cloud lifetimes are an important factor in determining the arm/inter-arm contrast in CO, but only in comparison to the mean time between passages of a spiral density wave. An important point of my work is that the lifetime of an individual cloud is not just the timescale for OB star formation. It may be as large as 3 or 5 times this value due to cloud-shuffling and inefficient destruction. In the inner regions of our galaxy, the spiral density wave timescale may be less than the cloud-shuffling time, so relatively low arm/inter-arm contrasts would be possible. It is true, however, that I still expect some delineation of spiral structure in carbon monoxide, because the primary cloud-formation mechanism that I have proposed will work in phase with a spiral density wave. I believe that this expectation is not in contradiction to the results of the Columbia Sky Survey Telescope.

*Townes:* For some time it has appeared that the variation of isotopic ratios from cloud to cloud requires the maintenance of some form of material integrity for clouds for at least as long as about $10^9$ years. Thus the lifetimes in the range $10^8$ years now suggested by Solomon and by the speaker, while going some distance from the approximately $10^6$ years which used to be frequently chosen, are still not quite long enough. Can you make any good estimate from your approach as to how long the material of large clouds would be approximately segregated?

*Elmegreen:* In the inner regions of our galaxy, near the 5 kpc ring, two processes combine to allow clouds to be very long lived, possibly as long as $10^9$ years or more. One is that the spiral density wave comes by a cloud before it has time to "shuffle" much more than one generation, so each cloud does not become completely disrupted by internal processes. In addition, the self-gravitational re-collection of cloud pieces that will occur in spiral arms has minimum opposition from galactic tidal forces at 5-6 kpc from the galactic center. Thus cloud formation or re-collection is more efficient, and cloud self-destruction is less effective, at 5-6 kpc than in the solar neighbourhood. The timescales are such that some clouds or cloud-pieces may never be completely destroyed at 5-6 kpc. This also may be true, but to a lesser degree, in the solar neighbourhood.

*Mouschovias:* Earlier speakers mentioned that observations show that the typical extent of a giant molecular cloud is about $10^2$ pc in the galactic plane. If you consider a tube of radius $\sim$100 pc, the tube must have a length larger than 1 kpc in order to contain your required $\simeq 5 \times 10$ $M_\odot$. Therefore, you need to move material along the tube over a distance of over 1 kpc, if you are to explain giant molecular clouds in this manner. Even if velocities of about 10 km $s^{-1}$ could be induced

https://doi.org/10.1017/S0074180900072545 Published online by Cambridge University Press

by self-gravity at these low densities - which is doubtful - you would still need at least $10^8$ years to form these clouds. Is that not too long a time?

*Elmegreen:* The primary collapse time of a supercloud formed by the self-gravity of a spiral-density-wave shock is calculated to be some 30 million years for our galaxy in the 5 kpc ring. This value was calculated with a shock compression-factor of about 9, and it does account for the elongated geometry. It is fast enough for significant collapse to occur before the gas emerges from the spiral-density-wave shock. After this initial condensation, the final collapse to molecular-cloud densities would presumably occur at a faster rate. I believe that the densities I calculated are slightly larger than your values, and may account for the difference in our time scales. A streaming velocity of 10 km $s^{-1}$, or slightly larger, does not contradict 21 cm line observations in our own galaxy or in other galaxies. Of course the gas will move from both ends of the perturbation to the center, so the largest excursion of any collapsing element will be only half the wavelength; this immediately reduces your estimate of $10^8$ years by a factor of two.