THE GALACTIC DENSITY WAVE, MOLECULAR CLOUDS AND STAR FORMATION

Frank N. Bash
Astronomy Department, University of Texas
Austin, Texas 78712, USA

ABSTRACT

A model has been devised for the orbits of molecular clouds in the Galaxy. The molecular clouds are assumed to be launched from the two-armed spiral-shock wave, to orbit in the Galaxy like ballistic particles with gravitational perturbations due to the density-wave spiral-potential and each cloud is assumed to produce an identical cluster of stars. A comparison of the model with observations suggests that each cloud radiates detectable $^{12}C^{16}O$ ($J = 1 \rightarrow 0$) spectral line radiation from birth to an age of 30 million years and that stars are seen in the cloud 15 million years after its birth. The model has been tested by comparing its predicted velocity-longitude diagram for CO against the observed one for the Galaxy and by comparing the model's predicted surface brightness in the UBV photometric bands against observed surface photometry for Sb and Sc galaxies.

1. INTRODUCTION

Work on star formation mechanisms is proceeding at a rapid rate. Herbst and Assousa (1977), Ögelman and Moran (1976) and Cameron and Truran (1977) cite evidence connecting supernovae with the formation of stars. Loren (1977) and Elmegreen and Lada (1977) cite evidence that star formation is triggered by an expanding HII region as it interacts with a dense cloud. Wielen (1973) and in several other papers has discussed questions related to density wave star formation. Bash, Green and Peters (1977) discuss evidence that the spiral density wave is causally related to star formation in the Galaxy. Seiden and Gerola (1978) have devised a stocastic model for star formation in galaxies which is capable of giving, at least, spiral arcs and possibly even 2-arm spirals of newly formed stars without invoking the density wave theory.

I believe that these various modes of star formation are not mutually exclusive. The obvious, basic 2-arm spiral symmetry seen in most Sa, Sb and Sc spiral galaxies must result from the galactic density wave, but the fraction of stars which it produces directly is unclear. It may produce

W. B. Burton (ed.), The Large-Scale Characteristics of the Galaxy, 165–172.

only a relatively small number of "primary" stars which, in turn, produce additional "secondary" stars through the supernova or expanding ionization front mechanisms. Since only massive, short-lived stars are believed to be effective in producing supernovae or large HII regions, these secondary stars will also be in a spiral pattern. The mechanism suggested by Seiden and Gerola (1978) may describe star formation in, for example, Sd galaxies; however, it seems incapable of producing the two smooth, wide spiral arms seen in the old disk stars as revealed in very red photographs of, e.g., M51 (Zwicky, 1955). These very red photographs seem to show the response of the old disk stars to the linear density wave.

2. DENSITY WAVE INDUCED STAR FORMATION

Bash and Peters (1976), Bash, Green and Peters (1977), and Bash (1978) have attempted to find observational evidence which connects the spiral density wave, molecular clouds, and star formation in the Galaxy. We have assumed that a spiral density wave exists in the Galaxy, that its current position, gravitational potential and pattern speed are the values fitted to HI 21-cm observations and to the positions and velocities of a group of 25 stars by Yuan (1969a, 1969b). We have also used the values of the gas velocities in the two-armed spiral-shock (TASS) wave given by Shu, et al. (1972) and Shu, Milione and Roberts (1973). We have assumed that molecular clouds are launched from the TASS wave with the predicted shock-wave velocities, and that they ballistically orbit in the Galaxy as perturbed by the spiral-arm potential. By integrating their orbits we can predict their positions and velocities as a function of time since they left the TASS wave. This time, called their dynamical age, is the independent variable in the integration of their orbits.

Bash and Peters (1976) concluded that the model ballistic-particle molecular-clouds whose dynamical ages are no more than thirty million years have the same values of predicted radial velocities as those observed for galactic CO. We suggested that some process must cause the CO-emitting molecular clouds to be no longer observable at ages greater than thirty million years, since the model predicts that older clouds have radial velocities which exceed any observed velocities.

Bash, Green and Peters (1977) tested the above result by looking for CO-emitting molecular clouds associated with young clusters of stars. We found that 90% of young clusters containing O-stars have associated CO emission, while less than 10% of the clusters whose earliest star lies between B0 and B4 have associated CO-emission. This result caused us to assume that molecular clouds launched from the TASS wave form star clusters or associations and that the thirty million year CO "cut-off" corresponds to the time in the cluster's life when the last O-star completes its evolution. Wheeler and Bash (1977) have suggested that perhaps a B0 star is the most massive star capable of becoming a supernova and that the first supernova explosion rids the clusters of its associated CO. Since we estimate that the main sequence lifetime of an B0 star is 15 million years, we concluded that about 15 million years elapse from the time a molecular cloud leaves the TASS wave until the stars begin to form. That star formation time is very close to the values inferred from observations of M51 (Mathewson, van der Kruit and Brouw, 1972) and of M81 (Rots and Shane, 1975 and Rots 1975) and computed by Woodward (1976).

3. STAR FORMATION AND UBV SURFACE BRIGHTNESS

Bash (1978) also computes the UBV surface brightness predicted by the model and compares it with the observations of Schweizer (1976). We assumed that each model-ballistic-particle is a molecular cloud which becomes an open star cluster 15 million years after leaving the TASS wave. For simplicity, this was assumed to be the only mechanism for star formation. The star cluster is assumed to continue in ballistic orbit around the Galaxy and, as it ages, the stars evolve. Each cluster is initially bright and blue due to the light of the early-type stars but, as the cluster ages, its light becomes dimmer and redder as the massive stars die. The distribution of stellar masses in each cluster was taken from observations (Taff, 1974 and Scalo, 1978) and the total mass in each cluster was adjusted to agree with the observed average surface brightness of M81. The orbit of each molecular cloud→star cluster was integrated for 100 million years. To represent the light of the Galactic disk, a smooth stellar disk with a radial brightness gradient was added and the disk colors, brightness and radial brightness gradient were taken directly from observations of external galaxies.

The model resembles the observations quite well except that the model's (U-B) and (B-V) colors were too blue by about $0\overset{m}{.}5$. However, it was pointed out that the evolution of the model cluster stars had been simplified by considering only their main-sequence phases and that was at least a part of the cause for the color disagreement.

4. RECENT WORK

We shall now report some new work completed after Bash (1978). The model, described above, has been improved by, a) including the giant and supergiant phases in the evolution of the model cluster stars and b) adding a linear density wave to the underlying disk. The computed and observed (U-B) and (B-V) colors now agree.

Bash (1978) describes a "cluster model 1". We now wish to allow the stars in cluster model 1 to evolve through the giant and supergiant phases. Only stars more massive than 3 $M_\odot$ leave the main-sequence in 100 million years which is the limit for our integration of the cluster orbits. Evolutionary tracks for stars of mass 15 $M_\odot$, 9 $M_\odot$ and 5 $M_\odot$ were taken from Iben (1967). Tracks for stars of mass 63 $M_\odot$, 40 $M_\odot$ and 25 $M_\odot$ come from Stothers (1963, 1964, 1965, 1966a, 1966b, 1968). Bolometric corrections were obtained from Panagia (1973), Morton and Adams (1972) and Johnson (1966), giving values of Mv. Spectral types were obtained from the same references as used for the bolometric corrections and (U-B) and (B-V) colors were obtained from Davis (1977) for stars earlier than G0 and Johnson (1966) for stars later than G0. The total mass of the stars in each model cluster was adjusted so that the average surface brightness of the model galaxy agreed with the values observed by Schweizer (1976) at distances 4.79 kpc and 6.67 kpc from the center of M81. The cluster mass which gives best agreement for cluster model 1 is 405 $M_\odot$/cluster. The absolute magnitude, Mv, and the (U-B) and (B-V) colors for cluster model 1 and for 100 million years after the stars turn on are shown in Figure 1.

Schweizer (1976) reports surface photometry measurements on six Sb and Sc galaxies. The surface photometry is measured in three color bands U, B_3 and O and, according to Schweizer, B_3 = B - 0.3 (B-V). His surface photometry is displayed for annuli, centered on the center of the galaxy, and with a variety of radii. The surface brightness around each annulus is displayed as a function of ϕ, the galactocentric azimuth, which increases in the direction of rotation. He defines the disk component as the surface brightness of a level line passing through the two dimmest points, separated by at least 90° in ϕ. The spiral arm component is defined as the average amount of light above the disk.

For the disk of our model galaxy we have adopted the surface brightness, colors, and radial gradient in brightness found by Schweizer (1976) for M81. To the disk we have added a linear density wave of the form

$$D \text{ (magnitudes)} = -A\ (1 + \cos\ [-2\phi + \Phi(R)\ ]\ ).$$

At the spiral arm minima, D = 0 and we see the smooth disk. At the spiral arm maxima, the disk brightness increases to the smooth disk value minus 2A magnitudes. The disk color is assumed to be everywhere the same, only its brightness changes. Cluster model 1 with its evolved stars (as described above) plus the value A = $0^m\!.2$, allows us to fit Schweizer's observations of the surface brightness and color of M81.

Figure 2 shows the results of the model calculations. The data are displayed in the same way as Schweizer (1976) displays his observational data. We have chosen to compute the surface brightness for three annuli at R = 4.79, 6.67 and 8.24 kpc from the center of the model of the Galaxy. The ordinate is absolute magnitude per square kiloparsec, M kpc^{-2}. (M kpc^{-2} + 36.57 = magnitude per square arcsecond.) The shapes of the surface brightness cuts across the arms, and the decrease in the apparent "noise" from U to V all resemble observed data in Schweizer's (1976) Figure 5c for M81. The average surface brightness in the model annuli computed in the U and B_3 filters are within 0.2 magnitudes/square arcsec. of Schweizer's observed values. The average peak height of the computed profiles above the disk brightness lie within 0.3 magnitudes/square arcsec. of Schweizer's observed values in the U and B_3 filters. The average width of the spiral arms, using Schweizer's measure, $\Delta\phi_{1/2}$, is 27°, very close to the average value he measured for M81. The arm width of the model arms does not drop rapidly to very small values at large radii, as Schweize observes, but unlike the predictions of the models which he quotes.

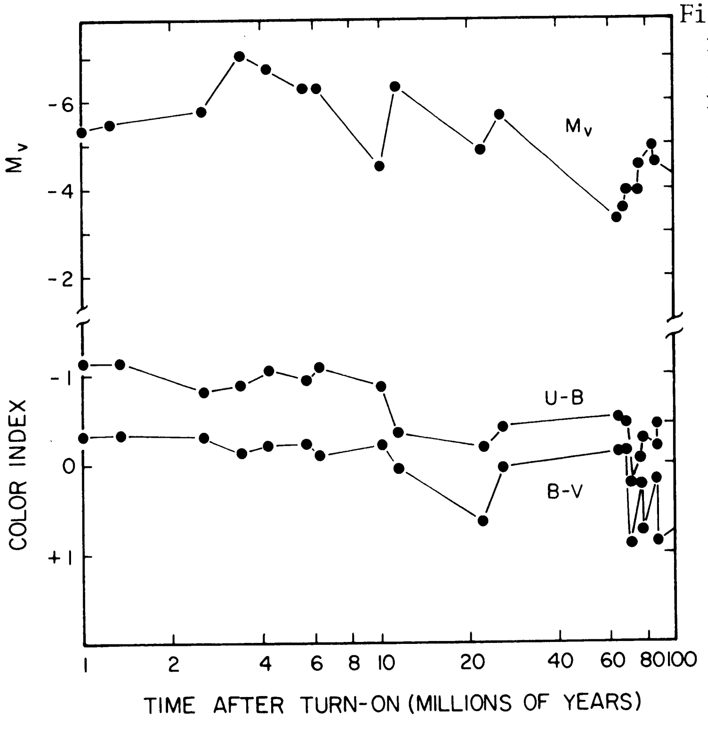

Figure 1. The absolute magnitude, Mv, and (U-B) and (B-V) colors of one model 1 cluster as a function of time after the stars turn on. Cluster model 1 contains 405 $M_\odot$ of stars.

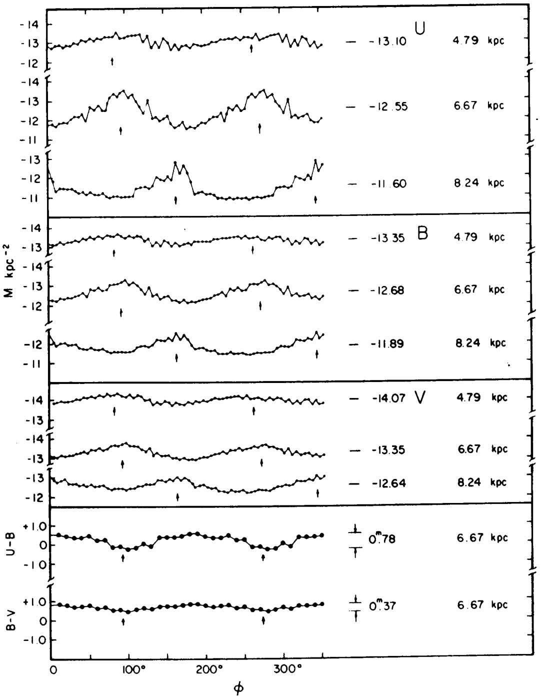

Figure 2. The UBV surface brightness of the model of the Galaxy in annuli of radius 4.79, 6.67 and 8.24 kpc from the center. The galactocentric azimuth, ϕ, increases from the Sun-galactic center line in the direction of galactic rotation. The average surface brightness around each annulus is shown just to the right of each trace and the colors around the R = 6.67 kpc annulus are shown at the bottom. The arrows mark the places where the annuli cross the centers of the density-wave arms.

The older model, reported by Bash (1978), gave similar agreement with Schweizer's (1976) observations. However, the colors of the spiral arms in our older model were bluer by about $0^m_.5$ than Schweizer's observed ones. The average colors of the spiral arms in the current model are (B-V) = +0.53 and (U-B) = -0.14. These colors are very similar to values Schweizer has observed for the galaxies in his sample. He finds that the average colors of the spiral arms in M81 are (U-B) = -0.17, (B-V) = +0.74. However, the average (B-V) color of the spiral arms in M99, M51 and M101 is +0.50. This color agreement has been achieved by including giant and supergiant phases in the evolution of the model cluster stars and by assuming that the disk stars exhibit a linear density wave of amplitude 0.2 ≃20% of the disk brightness.

The stellar birthrate averaged over the region where the model applies, 4 kpc < R < 11.4 kpc, required to fit the observations of M81 is 0.08 $M_\odot$ yr^{-1}. The birthrate is the product of the mass of each model cluster, the number of model birthsites and the number of clusters born at each per year.

5. SUMMARY

We have attempted to find observational evidence and a model which connects the density wave theory, molecular clouds and star formation. The model, which is constructed for the Galaxy, uses the density wave parameters fit to HI observations and stellar orbits and by assuming that molecular clouds are launched from the TASS wave and emit observable CO spectral lines for 30 million years, it is largely consistent with CO survey results. The model predicts that the CO radiation abruptly cuts off at 30 million years and such a cut-off is seen by observing CO associated with young star clusters. The model predicts the UBV surface brightness of the Galaxy but the stellar birthrate must be adjusted. It is fit to the observed average surface brightness of external spiral galaxies. The model can be adjusted to agree with observations of M81 and other galaxies; however, caution needs to be exercised in applying the stellar birthrate which this fit implies to our Galaxy since, for example, according to Rots (1975), M81 is well fit with a spiral of pitch angle 15° while the density wave fit to the Galaxy has a pitch angle of $6^\circ_.65$. However, the model gives spiral arms whose brightness, width and color agree well with values observed for Sb and Sc galaxies.

REFERENCES

Bash, F. N. and Peters, W. L.: 1976, Astrophys. J., 205, pp. 786-797.
Bash, F. N., Green, E., and Peters, W. L.: 1977, Astrophys. J., 217, pp. 464-471.
Bash, F. N.: 1978, Astrophys. J., in press.
Cameron, A. G. W. and Truran, J. W.: 1977, Icarus, 30, pp. 447-461.
Davis, R. J.: 1977, Astrophys. J., 213, pp. 105-110.
Elmegreen, B. G. and Lada, C. J.: 1977, Astrophys. J., 214, pp. 725-741.

Gerola, H. and Seiden, P. E.: 1978, Astrophys. J., in press.
Herbst, W. and Assousa, G. F.: 1977, Astrophys. J., 217, pp. 473-487.
Iben, I.: 1967, Ann. Rev. Astr. Astrophys., 5, pp. 571-626.
Johnson, H. L.: 1966, Ann. Rev. Astron. and Astrophys., 4, pp. 193-206.
Loren, R. B.: 1977, Astrophys. J., 218, pp. 716-735.
Mathewson, D. S., van der Kruit, P. C., and Brouw, W. N.: 1972, Astron. and Astrophys., 17, pp. 468-486.
Morton, D. C. and Adams, T. F.: 1972, Astrophys. J., 151, pp. 611-622.
Ögelman, H. B. and Moran, S. P.: 1976, Astrophys. J., 209, pp. 124-129.
Panagia, N.: 1973, Astron. J., 78, pp. 929-934.
Rots, A. H., and Shane, W. W.: 1975, Astron. and Astrophys., 45, pp. 25-42.
Rots, A. H.: 1975, Astron. and Astrophys., 45, pp. 43-55.
Scalo, J. M.: 1978, to appear in Protostars and Planets, ed. T. Gehrels (Tucson: University of Arizona Press).
Schweizer, F.: 1976, Astrophys. J. Suppl., 31, pp. 313-332.
Shu, F. H., Milione, V., Gebel, W., Yuan, C., Goldsmith, D. W. and Roberts, W. W.: 1972, Astrophys. J., 173, pp. 557-592.
Shu, F. H., Milione, V., and Roberts, W. W.: 1973, Astrophys. J., 183, pp. 819-842.
Stothers, R.: 1963, Astrophys. J., 138, pp. 1074-1084.
__________: 1964, Astrophys. J., 140, pp. 510-523.
__________: 1965, Astrophys. J., 141, pp. 671-687.
__________: 1966a, Astrophys. J., 143, pp. 91-110.
__________: 1966b, Astrophys. J., 144, pp. 959-967.
Stothers, R. and Chin, C.: 1968, Astrophys. J., 152, pp. 225-232.
Taff, L. G.: 1974, Astron. J., 79, pp. 1280-1286.
Wheeler, J. C. and Bash, F. N.: 1977, Nature, 268, pp. 706-706.
Wielen, R.: 1973, Astr. and AStrophys., 25, pp. 285-297.
Woodward, P. R.: 1976, Astrophys. J., 207, pp. 484-501.
Yuan, C.: 1969a, Astrophys. J., 158, pp. 871-888.
_______: 1969b, Astrophys. J., 158, pp. 889-898.
Zwicky, F.: 1955, Pub. Astr. Soc. Pacific, 67, pp. 232-236.

DISCUSSION

Solomon: The "CO emitting lifetime" of $3x10^7$ years which you give suggests that during most of a galactic rotation of $2x10^8$ years the gas is in some form other than molecules. However, the CO surveys of the Galaxy clearly show that 70%-90% of the gas is in molecules, particularly at 4-7 kpc where you are matching the observations. Where, and in what form, is the gas during the other $2x10^8$ years in your model? The connection between CO and HII regions in your model is a result of matching the CO ℓ,v diagram. This diagram maps temperature; hot molecular clouds are correlated with the presence of HII regions, as has been known for the past seven years. However, most of the mass in molecular clouds is not in hot regions, and most molecular clouds do not have strong heating sources. Therefore, your result appears to be a confirmation of the correlation of hot molecular clouds with HII regions, not a correlation of all molecular clouds with such regions.

https://doi.org/10.1017/S0074180900014418 Published online by Cambridge University Press

Bash: Our model assumes that CO-emitting molecular clouds are seen for only 3×10^7 years after they leave the spiral shock wave. They may just mean that such clouds are only observable there (say due to higher CO temperatures) and not that CO clouds only exist there. However, because the inferred presence of a large population of very long-lived CO molecular clouds from your work depends on assumed C/H ratios, the number of such clouds must be uncertain.

Kaufman: First, a question: How do you account for the excitation of hot CO during the 15×10^6 years before the stars turn on?

Second, a comment: The 30-million-year width of the observed hot CO distribution is comparable to the 1-kpc apparent width of the HII region spiral arms of Georgelin and Georgelin. So it seems that you and the Georgelins may be detecting the same type of galactic features. By restricting your analysis to star formation by spiral shocks, you must work very hard to make your theoretical arms as wide as the observed hot CO and HII spiral arms. This is especially so in view of the fact that Carson's opacities and stellar winds suggest that massive stars evolve towards the red even faster than the conventional O-star lifetimes. However, one can easily account for the width of the HII arms if spiral shocks are not the only star-forming mechanism in our Galaxy. Because there are a number of observations linking star formation to expanding HII regions and expanding SNR's, a model based solely on star formation in galactic shocks is incomplete. The observed spiral features are probably a composite of, first, stars formed by the spiral shock and, then, stars formed by shock waves from high-mass stars. The massive stars formed by the spiral shock act as a trigger for further star formation.

Bash: First, I believe that only some, perhaps a minority, of all stars are directly formed by the action of the spiral-shock wave. However, our model, which assumes (for convenience) that all stars form from the spiral-shock wave is capable of producing spiral arms as wide as the observed ones.

Second, I imagine that the CO is excited during the 15×10^6 years before the stars turn on basically by the collapse of the cloud.

Wielen: I understand that you favor the post-shock version of initial velocities. This is in contrast to our results that the pre-shock velocities give a better description of the observational results, especially in M51. How did you obtain the initial velocities, e.g., in M81?

Bash: The model discussed here is for our Galaxy and the predicted surface brightness was then compared to Schweizer's observations of M81. Post-shock velocities are required to give a model ℓ,v diagram for CO which agrees with the observed one.