STAR FORMATION, GIANT HII REGIONS AND SPIRAL STRUCTURE

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1. INTRODUCTION

The three topics outlined in the title I have been given for this contribution are each far too complex to be thoroughly reviewed in the short time available. Instead of trying to duplicate the relevant (28, 34, 35) Commission Reports in the Transactions of the IAU (R.M. West 1985), I shall review only briefly current results on the stellar content of giant HII regions and then continue towards recent developments of our ideas about the mutual interrelation of galaxy wide star formation and spiral structure. The goal is to emphasize the simultaneous need for descriptions of details and unifying approaches.

2. GIANT H II REGIONS

It is worthwhile to recall to one's mind the importance of the stellar content of giant H II regions (henceforth I will use the term OB clusters as a synonym) for studies of young populations in galaxies. These objects with typical masses of 10^6 $M_\odot$ in gaseous form and 10^5 $M_\odot$ in stars contain appreciable fractions of their parent galaxies most massive stars. Israel (1980) found that the brightest H II regions tend to dominate the thermal emission of late type galaxies, the five brightest contributing on the average 22 percent and even the single brightest on the average 10 percent. The extremely young OB cluster 30 Dor contains relatively more very massive short-lived O3 and O4 stars than the bulk of OB associations in the LMC (see Section 3). Similarly, the UV photometry of Hill et al. (1984) in M 101 shows that the 6 largest H II regions, viz. 12 percent of the individually measured OB clusters, generate 30 percent of the total flux obtained from the OB clusters and more than 15 percent obtained from the entire galaxy at 225 nm. Since giant H II regions and their ionizing OB clusters are found in star forming galaxies of all masses and types, e.g. irregulars, blue compact galaxies, dwarf spirals and giant spirals, their importance in studies of luminosity functions (LF), star formation rates (SFR) and initial mass functions (IMF) for stars more massive than about 15 $M_\odot$ is stressed.

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Reviews, compilations and recent results on various properties of giant H II regions and violent star formation bursts may also be found in Rosa (1983), Kennicutt (1984), McCall et al. (1985), Rosa and D'Odorico (1986).

3. STELLAR POPULATIONS IN GIANT H II REGIONS

Physical and structural properties of the nebular and stellar component of several giant H II regions in nearby galaxies have been compared by Gallagher and Hunter (1983), Kennicutt (1984) and by Terlevich and Melnick (1981) for more remote objects. Although a large range in total masses and luminosities is encountered, scaled versions of the 30 Dor prototype are applicable. Internal kinematics have been studied in detail by Rosa and Solf (1984) of NGC 604 in M 33 and by Hunter and Gallagher (1984) and by Skillman and Balick (1984) of several additional regions. The results indicate the mutual importance of stellar winds from OB stars, Wolf-Rayet (WR) stars, SN explosions and the hydrodynamics of cloud ionization for the mechanical energy input into the giant H II nebulae, questioning the picture of self-gravitating, virialized systems invoked by Terlevich and Melnick (1981).

The frequent presence of evolved stages of massive O stars in such OB clusters has been revealed in a large spectroscopic survey of 77 giant H II regions in 14 galaxies through the detection of the typical emission features of the late WN 7,8 and WC 5 stars in 30 percent of the H II regions observed (Rosa and D'Odorico 1986). The mixture of WR and very massive O stars is generally similar to that in the 30 Doradus complex, although evolutionary effects determine the detailed composition of the stellar population seen. If supernova explosions are the evolutionary fate of massive O stars the detection of supernovae and their remnants in the populous OB clusters should come as no surprise. The SN remnants in NGC 604 (Benvenuti et al. 1979), in an H II region in NGC 4449 (Blair et al. 1984) and possibly in the giant H II region NGC 5471 in M 101 (Skillman 1985) are examples. A strong correlation between the location of historical supernovae of type II and giant H II regions in M 83 and M 101 has been found by Richter and Rosa (1985). Spectra obtained at the positions of the historical SNe II in M 83 revealed the emission features of massive stars in the very advanced WC evolutionary stage. The latter two results, if interpreted under the hypothesis of coeval evolution in the OB clusters, indicate extremely high ZAMS masses ($> 30\ M_{\odot}$) for the progenitors of the M 101 and the M 83 SNe II (Rosa and D'Odorico 1986).

Attempts to determine ages, luminosity functions, (local) star formation rates and IMF parameters of OB clusters have been made by several authors using spatially integrated parameters, i.e. Balmer emission luminosity, blue or IUE UV luminosity, colors and low spectral resolution shapes of the integrated stellar light (e.g. Lequeux et al. (1981), Kennicutt et al. (1984), DeGoia-Eastwood (1985) and Terlevich and Melnick (1986)). General agreement exists about the fact that the

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spectra and the luminosities can successfully be explained by integrated spectra of large OB clusters with ages between 1 and 7 10^6 years and IMF's not radically different from the one in the solar neighbourhood. Population synthesis models calculated by Melnick et al. (1985) confirm the general insensitivity of the classical stellar population and evolution measures like UBV colours on ages, metallicity and mass loss rates of the ionizing stars in such extremely young OB clusters. The detailed comparison of the energy distribution and the spectral features in moderate resolution high signal to noise spectra from the far UV to the far red with synthetic spectra might be required to yield less ambiguous answers on exact ages, burst duration times, the frequency of multiple bursts of star formation within the OB cluster, of slopes and upper/lower mass limits of the IMF and of the dependence of these parameters on metallicity (Rosa and D'Odorico 1986).

The work mentioned above rests entirely on an a priori knowledge of the expected range of parameters (time scales, IM, evolutionary scenarios), in other words - we need to know at least one OB cluster in very detail. The large progress made into this direction for the stellar content of the 30 Dor OB cluster has been reviewed in detail by Walborn (1986). Firstly, the super-massive star hypothesis for R 136a has been dismissed by speckle interferometric resolution into at least 8 stellar components with magnitudes comparable to the single luminous O stars known in the cluster (Weigelt et al. 1985). Secondly, spectral classification exists now for almost 70 stars (Melnick 1985, Walborn 1986), of which no fewer than 15 are massive O3 stars, excluding the components of R 136a. Finally, the luminosity function of the cluster is now known in detail for more than 500 stars in the range $-7 < M_V < 0$ and the IMF deduced contains some 300 stars more massive than 20 $M_\odot$ and about 30 between 100 and 200 $M_\odot$. The slope of this IMF (1.0 +/- 0.4 for $M > 4\ M_\odot$) is not very different from the solar neighbourhood value (1.35 for $M < 10\ M_\odot$) (Melnick 1986).

To summarize, the results obtained in studies of large samples of remote OB clusters justify the application of results obtained in detailed investigations of a few nearby objects (30 Dor, NGC 604) as templates or prototypes class, in particular for population analysis from integrated spectra. They support star formation scenarios that associate OB star formation with intense, short time scale phenomena and disruptive processes for the interstellar medium. The local star formation rates, typically $10^5\ M_\odot$ in a volume of 20 pc diameter in 10^6 years (of order 0.1 $M_\odot$ per year), are only an order of magnitude lower than those of entire galaxies (a few $M_\odot$ per year). Since the evolutionary time scales of the most massive stars are only a few 10^6 years, both facts together pose severe constraints on star formation scenarios through the multitude of feedbacks present in form of radiation, winds and shock fronts in the parental cloud. These aspects have been reviewed by Silk (1986). Observable effects have to be expected as well from the high specific (in space and time) enrichment of the interstellar medium in nucleosynthesis products, in particular CNO elements (Rosa and Mathis 1985).

4. GLOBAL ASPECTS OF STAR FORMATION IN SPIRAL GALAXIES

Investigation of star formation on galaxian scales is driven by the desire to have physical, self-consistent descriptions and predictions of the stellar, gaseous, chemical and dynamical evolution of entire galaxies. To do so we have to know, with appropriate spatial resolution, how the ingredients and the products of recent star formation are distributed in a "typical" (here spiral) galaxy. Secondly, the proper description of the the dynamics is required, which is mostly determined by less luminous and even dark components, essentialyy the remnants of star formation throughout the galaxies entire history and eventually additional exotic dark matter (neutrinos etc.). And, finally, the delicate, complex network of causal relations between all processes involved will have to be understood. In the remainder of this contribution I shall concentrate on those aspects where considerable progress has been made towards such a comprehensive understanding.

5. SPIRAL PATTERNS AND STAR FORMATION

One of the major problems in modelling spiral galaxies is the difficulty to maintain a spiral pattern, once it has been generated, over a considerable fraction of a galaxies lifetime and for a reasonably small set of boundary conditions (excluding galaxies with strong bars). Models based on spiral density waves, though generally adopted, have been questioned because of the rareness of "grand design" spirals and because of the difficulty to interprete the detailed morphology of several nearby galaxies by star formation scenarios based on a rigid causal relation between star formation locii and a spiral density wave pattern.

Frequently used spiral arm tracers are giant H II regions in the visual and radio domain and giant molecular and neutral clouds in the radio regime. As Sanders et al. (1984) pointed out, it is clear that the immediate progenitors of OB stars must be spiral arm tracers as well as the stars and their ionized environments do, but none of these tracers is strictly confined to an idealized spiral arm pattern. Since it is even debated whether the distributions of small and giant H II regions are different as in the case of M 33, M 101 (Rumstay and Kaufmann 1984) or whether this is a statistical effect in a small sample and that a tendency of giant star formation sites to appear at particular locations is absent in larger samples (Elmegreen and Elmegreen 1983, Kennicutt and Hodge 1984), the analysis of such distributions cannot yet be expected to make conclusive decisions about the prevalence of different spiral arm models.

Evidently, a mechanistic star formation scenario forming, coagulating and compressing clouds in a spiral arm shock with unit probability is too simple. On the other hand, the spiral structure obtained in models with stochastic self-propagating star formation has been shown to be a sole result of chain-reaction processes occurring in a differentially rotating disk (Freedman and Madore 1984). Steps forward in the application of a feedback mechanism between star formation and spiral pattern have been made by Sellwood and Carlsberg (1984), who obtain transient but repeated spiral patterns only if processes mimicing star formation are included in the numerical simulations. Roberts and Hausman (1984) have added more detailed physcial prescriptions of star formation processes into N-body simulations of interstellar clouds moving in a spiral-perturbed gravitational field. Their results are intriguing in that (1) they obtain the grand design known from continuum models on large scales and (2) the more stochastic appearance of spiral arm morphology on small scales, as seen in real galaxies. While the global cloud morphology is more heavily affected by the galactic gravitational field characteristics, the actual distribution of young stellar associations on small scales is quite sensitive to the mean life times of the massive stars and to the susceptibility of their parental clouds to repeated star formation.

6. STAR FORMATION RATES AND HISTORIES, INITIAL MASS FUNCTIONS

Kennicutt and Kent (1983), Kennicutt et al. (1984), Gallagher et al. (1984) and Donas and Deharveng (1984) have determined current and historical star formation rates for large samples of spiral and irregular galaxies, based on integrated properties. The problems involved are discussed in detail by Hunter (1986, this volume). Freedman (1986) has discussed the stellar luminosity functions for a sample of nearby galaxies obtained from color-magnitude diagrams of the brightest resolved stars. An apparent constancy of star formation rates over the last 10^9 years is found, if the form of the IMF is assumed to be universal, consistent with current evidence (Scalo 1986). No obvious correlations of the value of the star formation rate with global parameters can be seen. In particular, the observations do not support a powerlaw dependence of star formation rates on surface gas density alone (Schmidt 1956). However, the above samples do not contain enigmatic cases, as e.g. interacting galaxies, which would explain why anemic spirals are not necessarily hydrogen poor and hydrogen poor spirals can show strong Balmer line emission (Kennicutt et al. 1984).

7. SELF-REGULATING STAR FORMATION IN LATE TYPE GALAXIES

At first glance it may seem illogical to find constant star formation rates and a universal IMF shape in normal galaxies, while a simple, but strong relation with global parameters of the parent galaxy is missing. Moreover, we have a wide variety of theoretical models all of which describe physically possible, although not yet fully satisfactory and self-consistent in every case, mechanisms to form clouds, to initiate star formation, to redistribute energy and mass, and to reorganize the ISM on all scales. However, it would be even more disturbing, if only a very few strong causal relations were at work and if it were only bad luck that the correct models cannot be isolated due to the missing "normal" case amongst all the peculiarities in the objects known so far.

Two concepts rarely employed till now in astronomy but highly successful in other natural sciences are called upon. Firstly, the replacement of one-way causal connections by feedback mechanisms. And secondly the finding that in an overwhelming number of cases order and structure seen on large scales are found to be the result of complex feedback cycles governing huge numbers of stochastic processes. Successful application of these concepts on small scale star formation describe the mutual stimulation and inhibition of star formation by preceding events of OB star formation in a single cloud complex (e.g. Elmegreen 1979) and the delicate process of long sustained low rate star formation in open cluster formation (e.g. Elmegreen and Clemens 1985).

Franco and Shore (1984) and Dopita (1985) have applied the above concepts to descriptions of self-regulated star formation on galaxian scales. Although many of the details remain to be filled with self-consistent theoretical models of the energy, mass and luminosity redistribution in the interstellar medium, they successfully explain total star formation rates and mass consumption rates, velocity dispersions in the molecular cloud populations, and radial gradients in star formation rates across spiral galaxies. The regulating agent in both models is the energy and momentum input of young high mass and of old low mass stars into the interstellar medium, maintaining a gas pressure in a stochastic sense. Schmidt's Law can be obtained in localized regions where the surface density of gas varies as a power law of the surface mass density. The ad hoc assumptions of gas infall or outflow made in models of chemical evolution of galaxies (e.g. Diaz and Tosi 1984) could eventually be incorporated in such a global view. A gaseous disk pressurized by star formation might be replenishing itself on the basis of need from a (not yet seen) gaseous halo. In galaxies with small total masses or in larger systems during runaway star formation the build up of overpressure could actually shut down the current star formation by a depletion of fuel, be it only by inhibiting the formation of cold dense clouds in a sufficient number. Enigmatic galaxies appear in this description whenever the delicate regulating mechanisms are disturbed for one single reason or for many others, e.g. by gravitational interaction of galaxies, by stochastic fluctuations in the distribution of the ingredients, by gas inflow or outflow in nuclear regions.

8. CONCLUSIONS

Combining our knowledge on spiral structure and on global star formation scenarios, the intriguing aspect lies in the possibility that interactions between various components of a galaxy are fundamental in determining both the cloud and star formation on small scales, and the large scale spiral structure. If star formation scenarios are really that complex on all scales, the critical range of parameters over which individual physical processes have to made work in self-consistent theories is relaxed because not every scenario is required to explain the entire system under consideration. Observationally, however, the amount of generic information on individual parameters that can be obtained from a few global parameters observed in small samples of galaxies is reduced. We still have only marginal information on the luminosity functions in galaxies, in our own galaxy due to extinction and aspect peculiarities, in Local Group galaxies due to spatial confusion and faintness of the individual stars. Similar to the work on OB clusters in giant H II regions, studies of large samples of "normal" galaxies will have to be supplemented with deep investigations of the stellar populations in nearby galaxies, a task for which the Hubble Space Telescope is well suited.

REFERENCES

Benvenuti, P., D'Odorico, S., Dumontel, M.: 1979, Astrophys. Space Sci. 66, 39
Blair, W.P., Raymond, J.C., Fesen, R.A., Gull, T.R.: 1984, Astrophys. J. 279, 708
DeGoia-Eastwood, K.: 1985, Astrophys. J. 288, 438
Diaz, A.I., Tosi, M.: 1984, M.N.R.A.S. 208, 365
Donas, J., Deharveng, J.-M.: 1984, Astron. Astrophys. 140, 325
Dopita, M.A.: 1985, Astrophys. J. 295, L5
Elmegreen, B.G.: 1979, Astrophys. J. 231, 372
Elmegreen, B.G., Elmegreen, D.M.: 1983, M.N.R.A.S. 203, 31
Elmegreen, B.G., Clemens, C.: 1985, Astrophys. J. 294, 523
Franco, J., Shore, S.N.: 1984, Astrophys. J. 285, 813
Freedman, W.L., Madore, B.F.: 1984, Astrophys. J. 280, 592
Freedman, W.L.: 1986, in "Luminous Stars and Associations in Galaxies", IAU Symp. 116, eds. C. de Loore, A. Willis and P.G. Laskarides, Reidel, Dordrecht (in press)
Gallagher, J.S., Hunter, D.H.: 1983, Astrophys. J. 274, 141
Gallagher, J.S., Hunter, D.H., Tutukov, A.V.: 1984, Astrophys. J. 284, 544
Hill, J.K., Bohlin, R.C., Stecher, T.P.: 1984, Astrophys. J. 277, 542
Hunter, D.H., Gallagher, J.S.: 1985, Astron. J. 90, 80
Israel, F.P.: 1980, Astron. Astrophys. 90, 246
Kennicutt, R.C., Kent, S.M.: 1983, Astron. J. 88, 1094
Kennicutt, R.C.: 1984, Astrophys. J. 287, 116
Kennicutt, R.C., Hodge, P.W.: 1984, PASP 96, 944
Kennicutt, R.C., Bothum, G.D., Schommer, R.A.: 1984, Astron. J. 89, 1279
Lequeux, J., Maucherat-Joubert, M., Deharveng, J.M., Kunth, D.: 1981, Astron. Astrophys. 103, 305
McCall, M.L., Rybski, P.M., Shields, G.A.: 1985, Astrophys. J. Suppl. 57, 1
Melnick, J., Terlevich R., Eggleton, P.P.: 1985, M.N.R.A.S. 216, 255
Melnick,J.: 1986, in "Star Forming Dwarf Galaxies and Related Objects", eds. D. Kunth, T.X. Thuan and Tran Thanh Van, Paris (in Press)
Melnick, J.: 1986, Astron. Astrophys. 153, 235
Richter, O.-G., Rosa, M.: 1984, Astron. Astrophys. 140, L1
Roberts, W.W., Hausman, M.A.: 1984, Astrophys. J. 277, 744
Rosa, M.: 1983, in "Highlights of Astronomy", Vol. 6, ed. R. West, p. 625

Rosa, M., Solf, J.: 1984, Astron. Astrophys. 130, 29
Rosa, M., Mathis, J.S.: 1985, in "Production and Distribution of C,N,O Elements", ESO Workshop, eds. I.J. Danziger, F. Matteucci and K. Kjaer, ESO Garching, p. 207
Rosa, M., D'Odorico, S.: 1986, in "Luminous Stars and Associations in Galaxies", IAU Symp. 116, eds. C. de Loore, A. Willis and P.G. Laskarides, Reidel, Dordrecht (in press)
Rumstay, Kaufman : 1983, Astrophys. J. 274, 611
Sanders, D.B., Scoville, N.Z., Solomon, P.M.: 1985, Astrophys. J. 289, 373
Scalo, M.: 1986, in "Luminous Stars and Associations in Galaxies", IAU Symp. 116, eds. C. de Loore, A. Willis and P.G. Laskarides, Reidel, Dordrecht (in press)
Schmidt, M.: 1956, Astrophys. J. 129, 243
Sellwood, J.A., Carlsberg, R.G.: 1984, Astrophys. J. 282, 61
Silk, J.: 1986, in "Luminous Stars and Associations in Galaxies", IAU Symp. 116, eds. C. de Loore, A. Willis and P.G. Laskarides, Reidel, Dordrecht (in press)
Skillman, E.D.: 1985, Astrophys. J. 290, 449
Skillman, E.D., Balick, B.: 1984, Astrophys. J. 280, 580
Terlevich, R., Melnick, J.: 1981, M.N.R.A.S., 195, 839
Terlevich, R., Melnick, J.: 1986, M.N.R.A.S., in press
Walborn, N.P.: 1986, in "Luminous Stars and Associations in Galaxies", IAU Symp. 116, eds. C. de Loore, A. Willis and P.G. Laskarides, Reidel, Dordrecht (in press)
Weigelt, G., Baier, G., Ladebeck, R.: 1985, in "The Messenger", Vol. 40, ESO Garching, p. 4.
West, R.M.: 1985, Reports on Astronomy, Transactions of the International Astronomical Union, Vol. XIXA, Reidel, Dordrecht