STAR FORMATION BURSTS IN GALAXIES

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ABSTRACT. We review the tracers of star formation in galaxies and show how they demonstrate the presence of bursts of star formation in various astrophysical contexts: large extragalactic HII regions in spiral and irregular galaxies and in blue compact galaxies, nuclei of some galaxies, extended star formation in other galaxies. We show that strong bursts seem to occur mainly in interacting galaxies. A few comments are made about the theory of such phenomena.

1. INTRODUCTION

A surprise of modern astrophysics is that star formation in galaxies may occur in an irregular and sometimes quasi-explosive way, rather than smoothly and quietly. This is true at least for the stars more massive than a few solar masses. We know very little about the formation of low-mass stars, even in our Galaxy, since it is very difficult to observe; the present consensus is that it takes place rather quietly in cold molecular clouds and is not generally coeval with the formation of higher-mass stars (see e.g. Silk, 1985). This paper is a short review of the evidence for bursts of massive star formation and of their properties. We first discuss briefly the observational tracers of star formation, then describe quasi-explosive star formation in giant extragalactic HII regions, and in more extended regions of galaxies. The role of interaction between galaxies is emphasized. A few remarks on theoretical aspects are given as the conclusion.

2. TRACERS OF STAR FORMATION

The present-day massive star formation rate (PDMSFR) in a galaxy, or part of a galaxy, can be derived in several ways (for a more extensive discussion, see Lequeux, 1985, 1986).

Direct star counts are available only for 13 nearby irregular galaxies, which form certainly the most unbiased sample for which the PDSFR

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can be determined. The results are consistent with a *global* PDMSFR per unit mass of gas approximately constant within a factor 2-3, and an initial mass function (IMF) with little significant variations. Clearly those galaxies are not experiencing at present a major burst of star formation although they may contain *local* bursts (e.g. 30 Dor in the LMC). Observations with the Hubble Space Telescope will allow to obtain similar data on more galaxies and more distant ones, as well as inside supergiant HII regions: in the latter case, data exist at present only for 30 Dor in the LMC (Moffat et al., 1985; Melnick, 1985).

The Lyman continuum flux is a good measure of the number of O stars, which are of course very young, massive objects. It can be derived (with some difficulties) from the thermal radio continuum flux or from the intensity of hydrogen recombination lines. Care should be taken to ascertain that the ionization is due to stellar radiation and not to some non-thermal far-UV continuum. Diagnostics exist (see e.g. Binette, 1985) but the relevant observations may not be available, and the results claimed concerning the *liners* (galactic nuclei with narrow emission lines) may sometimes be ambiguous. Hα emission surveys have been used by several authors (see Hunter and Gallagher, 1985; Kennicutt et al., 1984 and references herein) to discuss the correlations of the PDMSFR with several parameters of the galaxies. However some of the samples may be biased by starburst galaxies.

The far IR emission results from re-radiation of stellar light absorbed by interstellar dust. In a galaxy which does not form stars especially actively the ratio L_{IR}/L_B (L_{IR} being the total far-IR luminosity and L_B the total luminosity in the B band, in solar units) is of the order of 1 at most and the dust is rather cold (de Jong, 1985). Any galaxy with $L_{IR}/L_B >> 1$ and which has hot dust is likely to experience active star formation; the heating of the dust is dominated by the radiation of the most massive stars, and the efficiency of conversion of their radiation into far-IR emission is always very good, better than 0.5. Thus far-IR observations are an excellent way to detect starburst galaxies. The existence of galaxies with major bursts came indeed as one of the surprises of the IRAS observations.

The far-UV emission is dominated by young main-sequence stars with masses $\gtrsim 3\ M_\odot$, except for early type galaxies. Thus far-UV surveys are as good as far-IR surveys to detect starburst galaxies, with however the drawback that the far-UV radiation is very sensitive to interstellar extinction.

Other tracers of PDMSFR have also been used, e.g. the radio non-thermal emission or the near-infrared flux; however, their use may be ambiguous and should be discussed critically (see for the near-IR Campbell and Terlevich, 1984). As to the *colors* of galaxies, they certainly indicate when they are very blue the presence of a star burst but they are difficult to use quantitatively when they are not extremely blue (see e.g. the discussion by Searle et al., 1973).

3. STAR BURSTS IN EXTRAGALACTIC HII REGIONS

Supergiant HII regions exist especially in the external parts of Sc galaxies (e.g. NGC 604 in M33, NGC 5461 and 5471 in M101) and in irregular galaxies (e.g. 30 Dor in the LMC, CM 39 in NGC 4449). Blue compact galaxies are (often dwarf) irregular galaxies which are completely dominated by such an HII region. It is possible using the tracers described in the previous section to derive quantitative properties of these objects. For example, 30 Dor contains no less than $\overline{\sim}$ 600 O stars and CM 39 in NGC 4449 about 30 000 such stars (see Lequeux et al., 1981). The IMF looks normal or somewhat flat, with dependence on the metal abundance (Viallefond et al., 1982); the claimed evidences for supermassive stars (R 136 in 30 Dor) have now vanished (Weigelt and Baier, 1985). It is not easy to trace the history of massive star formation in these HII regions. They often seem to contain evolved stars like red supergiants (Campbell and Terlevich, 1984) or Wolf-Rayet stars (d'Odorico et al., 1983; Kunth and Joubert, 1985); that the star formation does not occur in a single, very short duration event is also suggested by preliminary spectral synthesis of UV spectra (Thuan, 1985) and by the generally low values of the equivalent width of the Balmer lines in emission (proportional to the ratio of O stars to low-mass or evolved stars: see e.g. Viallefond and Thuan, 1983). Unfortunately the large number of free parameters, as well as uncertainties in the interstellar extinction, precludes for the moment more quantitative conclusions.

The relationship between the location and properties of these star bursts and of their parent interstellar gas complexes is interesting. Tight correlations have been found between several parameters (Viallefond et al., 1982) which have implications on the properties of star formation. Obviously the rate of star formation is so high in many such objects that the lifetime of the complexes must be less than a few 10^7 years. An interesting fact is that all supergiant extragalactic HII regions, including blue compact galaxies, are similar in all these respects (Viallefond et al., 1982; Viallefond, 1985).

4. STAR BURSTS AT GALACTIC SCALES

Statistical data are becoming available concerning the frequency of occurrence of star bursts that are intense enough to affect strongly the global properties of galaxies. A first result is that they must be rare. For example, the integrated UV flux data discussed by Donas and Deharveng (1984, 40 galaxies) and by Donas (1985, 104 galaxies) simply show a good correlation (within a factor < 3) between the PDMSFR and the mass of gas, with no galaxy with an exceptionally strong burst. Similarly, the far-IR observations made by IRAS of an optically complete sample of 165 galaxies from the Revised Shapley Ames Catalogue reveal only 12 galaxies with $L_{IR}/L_B > 1$, and the upper value of L_{IR}/L_B is only 5 (de Jong et al., 1983); the IRAS survey of the Virgo cluster galaxies yields similar results (de Jong, 1985).

Star burst galaxies are found through very blue colors or strong emission lines, or strong far-IR flux from the IRAS survey. In the IRAS minisurvey (Soifer et al., 1983), L_{IR}/L_B ranges up to 50. Exceptional, well studied examples are Mk 231, NGC 6240 or Arp 220 = IC 4553, with $L_{IR}/L_B \overset{\sim}{>} 100$. These galaxies have $L_{IR} \overset{\sim}{>} 2\ 10^{12} L_\odot$, exhibit a PDMSFR in stars with $M > 10\ M_\odot$ of almost 1000 $M_\odot\ yr^{-1}$ (assuming a continuous star formation). It is clear that such a rate cannot be sustained for more than a few 10^7 years, given the limited amount of gas available for forming stars.

The geometry of the burst appears to vary from galaxy to galaxy. In some cases it is restricted to a small central region, e.g. within a radius of 280 pc for NGC 7714 (Weedman et al., 1981); but the extent may reach a few thousand parsecs (see e.g. Telesco and Gatley, 1984, for NGC 3310), and even the whole face of the galaxy in exceptional cases.

It appears that interaction in pairs of galaxies is very efficient in triggering these giant bursts of star formation. Interacting galaxies are stronger X-ray (Fabbiano et al., 1984) and radio (Condon, 1983) emitters than isolated galaxies. The fraction of multiple systems is exceptionnally high in the IRAS minisurvey sample, 1/8 to 1/4 of all galaxies. Many of the strongest starburst galaxies are known to be interacting systems or mergers. Well-studied cases are Arp 91 = NGC 5493 + 5494 (Jenkins, 1984), Mk 171 = Arp 299 = IC 694 + NGC 3690 (Gehrz et al., 1983; Augarde and Lequeux, 1985; Telesco et al., 1985), but there are many others. Actually one may even speculate that all the strong starburst galaxies are interacting systems, but we do not know enough to be sure.

Another open question is the shape of the IMF of stars created in these star bursts. Surprisingly enough, and in contrast with many extragalactic HII regions, their line emission spectrum and their far-UV stellar spectrum often do not indicate the presence of very massive stars (for example: Augarde and Lequeux, 1985, find an IMF truncated at about 35 $M_\odot$ in Mk 171). On the other hand, there cannot be a large amount of low-mass stars formed in these bursts: if this was the case, the available gas would be consumed in an incredibly short time. In Mk 171, spectroscopy suggests that there are not many stars with $M < 20\ M_\odot$ (Augarde and Lequeux, 1985). Clearly this problem deserves further studies.

5. THE ORIGIN OF STAR BURSTS

Why are massive stars sometimes formed in such giant bursts? This question has not received a definitive answer, although a hint towards it is given by the fact that these bursts appear to be associated with large-scale disturbances in the gas such as density waves, cloud collisions (?) and tidal galaxy encounters. Very recently Scalo and Struck-Marcell (1985) have proposed and interesting theory, which is based on the Oort model for interstellar cloud evolution and star formation. In this model, interstellar clouds coalesce into larger clouds that form massive stars; the newly-born stars disrupt these clouds into smaller entities; a refinement is that, when the relative kinetic energy of the collision between clouds exceed their binding energy, they fragment instead of merging together. Assume that in a galaxy at equilibrium a perturbation occurs, e.g. an increase of density. If there was no time lag in star formation, the galaxy would respond immediately by forming more stars as a consequence of the increase of the cloud coalescence rate; these stars would disrupt the clouds more efficiently and the system would return to equilibrium: we would not see a strong burst of star formation. However, there is actually a time delay between the formation of massive clouds by coalescence and the time when they are disrupted by the energetic events following massive star formation. If this time delay τ_d is long enough with respect to the characteristic time between cloud collisions τ_c at equilibrium, the perturbed system overcomes equilibrium and there is time to build very massive clouds before star formation occurs: because of the size of these clouds, there will be a star burst. The cloud disruption which follows the burst will be so efficient that equilibrium will be overpassed in the other direction; a cyclic behavior may set in, at least in theory: the corresponding critical value of τ_d/τ_c is 1/3. For larger $\tau_d/\tau_c \sim 3$, multi-periodic and chaotic behavior occurs. In practice, it seems that the condition for bursts to be possible is $\tau_d/\tau_c \gtrsim 1$. The solar neighborhood is marginal in this respect, and star-formation may be more or less self-regulated (this case is described e.g. by Dopita, 1985). Density enhancements at the crossing of a density wave may decrease τ_c enough for the system to become unstable: the perturbation given by the wave itself or any other, may trigger the formation of a very massive cloud by coalescence, then a starburst which itself produces a supergiant HII region. Larger-scale star bursts may also be triggered by the perturbation created by a tidal encounter between galaxies, provided that the condition $\tau_d/\tau_c \gtrsim 1$ is already fulfilled.

This model also allows interesting predictions which appear to be in reasonable agreement with the observations of starburst galaxies. The blue compact galaxies remain to be discussed in this context when better data become available.

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