Rates of galactic star formation

A remarkably simple argument successfully accounts for the rate of star formation in different galaxies. The snag is that the timescale is uncomfortably short.

How could star formation be infectious, or autocatalytic, "catching" in the vernacular? Simple prejudice says that such a mechanism is too anthropomorphic to be real. But the simple sight of a spiral galaxy such as that of the Milky Way will show that the pattern of star images, but especially that of new stars, has a clumsiness that suggests their congregation. The mass of stars in the Orion nebula argues the same case. The objective way out of this dilemma is to follow Schmidt (originator of the fast sky-camera) in supposing that the rate of star formation is somehow a function of the density of the raw material, interstellar gas. Obviously the functional relationship cannot be linear, for then the ratio of stellar mass to that of the immediately surrounding gas would be uniform in space. Schmidt (*Ap. J.* **129**, 243; 1949) suggested that the rate of star formation might be proportional to the square of the density of interstellar gas, or something like that.

Michael A. Dopita, from the Mount Stromlo and Siding Spring Observatories, who has a better autocatalytic idea, points out (*Ap. J.* **295L**, 5; 1985) that no relationship of the type proposed by Schmidt can explain why the Smaller Magellanic Cloud has only one fifth as much mass locked up in stars, per unit mass of gas, as has the Larger Magellanic Cloud. Infection, autocatalysis or positive feedback in star formation is his solution.

Suggestions that star formation may stimulate further star formation are far from novel. The mechanics of such a process are easily described. Newly formed stars will heat and even ionize the immediately surrounding interstellar medium, while those massive enough to run through their evolution quickly to form supernovae will add hot material to their environment. The result is that the interstellar medium is filled with hot gas in a set of circumstances, far from equilibrium, in which the colder material in the environment is compressed into clumps that may be massive enough to collapse under their own weight into proto-stars and eventually stars. Dopita refers to several explicit accounts, going back to the late 1970s, of how such a mechanism may account for observed properties of galaxies.

His own contribution is what he calls a "law of star formation" to replace that originally suggested by Schmidt. Time will tell whether it provides a sufficient ex-

planation of the variation of the rate of star formation from one galaxy to another as well as from place to place within a single disk-shaped galaxy. But its immediate virtue is the simplicity of its argument.

To make sense, a law of star formation must link the observed rate of star formation with something else that can be observed. Dopita settles for the surface brightness of neutral hydrogen of a galaxy, or of a part of it, which the radioastronomers are able to measure directly. The essential link between these quantities is simply that of kinetic theory, that the mean squared velocity of the gas is proportional to the pressure.

Dopita's argument then starts from the assumption that the interstellar gas pressure is a linear function of the two quantities representing the mass density of stars and the rate at which that variable changes with time as a consequence of star formation. In gas-rich galaxies (such as both the Magellanic clouds) but also in other circumstances, the rate of star formation will be the dominant determinant of interstellar gas pressure. In those circumstances, Dopita concludes, the total rate of star formation in a galaxy should be proportional to the product of its total mass and the surface gas density (in grams per cm^2 , for example).

The prescription seems to work remarkably well. At least on a log-log plot (of the rate of star formation and the product of total mass and surface gas density), both the Magellanic clouds, our own galaxy and a score of other gas-rich galaxies lie within a factor of less than 10 of a straight line, which is probably as much as can be expected for quantities such as the rate of star formation whose measurement is more a matter of inference than of observation. Certainly the result will be taken as an explanation of why the Smaller Magellanic Cloud has many fewer stars than its companion satellite galaxy — its mass is smaller.

The more typical case in which the interstellar gas pressure is a function both of the rate of star formation and of the density of pre-existing stars leads to a more complicated but still simple relationship. One necessary step in the argument is to estimate the fraction of the material incorporated into new stars which remains locked up in them. They must be objects not so massive that they form supernova explosions. The result, however, is a first-order linear differential equation for the

surface density of gas as a function of time. Integration leads directly to an expression for the surface gas density as an exponentially decreasing function of time which, significantly, does not decrease to zero but, rather, to a non-zero value. In other words, even in the galaxies most productive of new stars, there will always remain a certain amount of gas that is not incorporated into stars.

Again, the agreement with observation is good. The surface density of gas as a fraction of the total surface density of a galaxy should be a straight-line linear function of the ratio of the star-formation rate to the total mass of stars, either for an entire galaxy or for part of it. In the sample of galaxies Dopita uses for the comparison, the only two galaxies that do not lie near the curve are, in a sense, exceptions that "prove the rule" — other evidence suggests that they have recently accreted gas from some extragalactic source, and are thus artificially young.

Dopita himself says it is remarkable that "such a simplistic" model should give such a good fit. He also points to what may be the most uncomfortable consequence of the argument, the short timescale for galactic evolution implied by the constants in the model, determined by the best fit of the observations with the predictions. Most galaxies, on this basis, are using up their gas content on a time scale which is short, on the order of 1,000 million years, compared with the time scale of the Universe. Dopita is again quick to point out that this difficulty has arisen previously, most notably in the work of the late B.M. Tinsley and her colleagues but specifically in work such as that of R.C. Kennicutt (see *Ap. J.* **272**, 54; 1983), in which ultraviolet emission from hydrogen is used as a direct index of star formation.

On the face of things, this implies that the history of the present era of star formation in isolated disk galaxies is shorter than has previously been assumed and that, for some galaxies, the renewal of the stellar population may have only a short way to go. The puzzle is an important conundrum whose resolution is nevertheless not entirely beyond the bounds of possibility. Plainly the Dopita law does not take account of all the possibilities. But any explanation can only further complicate the difficulty of learning enough about the evolution of galaxies to tackle the question of the evolution of the Universe as a whole.

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