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Star Formation at High Redshift*

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Abstract

The observations relevant to star formation at high redshift are reviewed including radio galaxies, quasars, IRAS objects, and QSO emission and absorption line regions. Low redshift counterparts associated with starburst galaxies are discussed. The relation of galaxy formation, starbursts, and active galaxies and quasars is briefly reviewed. The role of feedback in galaxy formation and massive star formation is briefly analysed.

1. Introduction

The subject of star formation at high redshift is one where many different observations and astrophysical insights are brought to bear. Almost nothing is certain in this field, but there are a number of interesting constraints and reasonably well-posed questions that can be stated. The discussion here will include QSO emission and absorption lines, high redshift images of quasars and radio sources, blue fuzzy objects seen at faint magnitudes, clusters with cooling flows and E+A type galaxies, starburst galaxies and merging and interacting systems.

The physical conditions that we will try to derive in these objects will include the ambient pressures, the magnetic field strength, the radiation field characteristics, the dust content, the supernova rate, and the presence of molecules such as molecular hydrogen. These parameters all may have some bearing on star formation as we understand it locally. I will not be able to include here a review of the state of star formation theory, but refer instead to the excellent review by Shu *et al.* (1987) and the recent conference on star formation edited by Lada and Kylafis (1992).

Let us now briefly examine the above-mentioned objects in turn.

2. Quasar Emission Lines

The remarkable point here is that there is no real difference seen in QSO emission line spectra seen at high and low redshift. Note that at redshifts of $z \sim 5$ the universe is only $\sim 10^9$ yr old. Of course we are seeing the very inner ~ 10 pc or so of the QSO and the mass of the broad line region clouds is only of order

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$10^2 M_\odot$. However, the metallicities seem to be of solar abundance even at this early time and therefore star formation must have occurred here. As noted by Turner (1991) and Efstathiou and Rees (1988), for a massive black hole of order $\sim 10^8$–$10^9 M_\odot$ to form it is probably necessary for a galaxy of order $\sim 10^2$ times this mass to be forming around it. One interesting point discussed here at this Workshop is that it may eventually be possible to put interesting lower limits on the ages of older stars from various elemental lines in QSO emission line spectra and then compare them with the cosmological ages determined from constraints on the Hubble constant and the deceleration parameter of the universe.

3. QSO Absorption Lines

There are a number of important statistical studies of QSO absorption lines and a recent summary has been given by Boksenberg (1991). The number of CIV absorbers increases with time from redshift 1·25–3·3 by about a factor ~ 3. This is probably associated with an increase in the overall metallicity produced by star formation at these epochs. The metal absorbers studied by Bergeron and Boisse (1986) seem to be associated with starburst outflows which probably consist of supernovae-driven metal-rich superwinds (Heckman *et al.* 1990) associated with star formation rates of $\sim 10^2 M_\odot\,\mathrm{yr}^{-1}$. For the massive damped Lyman-alpha clouds the abundances of Zn and Cr give us significant constraints on the metallicity ($\sim 10^{-1}$–$10^{-2} Z_\odot$) and a dust to gas ratio which is approximately 10% that found in the solar neighbourhood. The inferred star formation rate is $\sim 1 M_\odot\,\mathrm{yr}^{-1}$ (Hunstead *et al.* 1990). The other remarkable fact about the intergalactic medium is that it is completely ionised and although the source of that ionisation is under debate it could be due to star formation at redshifts of order ~ 10.

4. High Redshift Radio Galaxies

These radio galaxies differ from their low-redshift counterparts in that the extended radio lobes, the optical continuum and emission line structures are all roughly aligned (Chambers 1990). The ages of the stellar continuum seem to consist of an old population $\sim 3\times 10^9$ yr and a young burst population 3×10^8 yr. The latter was probably triggered by the latest radio jet outburst from the nucleus. The inferred star formation rates are of the order 100–1000$M_\odot\,\mathrm{yr}^{-1}$ (Charlot 1992). The Lyman-alpha line is emitting $10^{44}\,\mathrm{erg\,s^{-1}}$ and the overall ionising flux is of order 10^{55} photons s^{-1}. Linewidths are of order $\sim 10^3\,\mathrm{km\,s^{-1}}$ corresponding to virial masses of $\sim 10^{12} M_\odot$. There is CIV seen in narrow band images extending over ~ 100 kpc showing the effect of large scale enrichment (McCarthy *et al.* 1990). The inferred pressures are of order $\sim 10^{-10}\,\mathrm{dyne\,cm^{-2}}$ corresponding to equipartition magnetic field strengths of order 10^{-4} G. The mass in cool gas clouds is very approximately $10^9 M_\odot$ and that of the hot confining medium at the virial temperature of 10^6 K has an approximate mass of $\sim 10^{11} M_\odot$. The main mechanisms for triggering star formation here involve the propagation of a jet and/or radio lobe through a multiphase medium surrounding the newly formed galaxy (Rees 1989; De Young 1990; Daly 1990; Begelman and Cioffi 1989).

5. High Redshift QSOs

From continuum and spectral studies of the nebulosity around radio loud quasars Heckman *et al.* (1991*a*, 1991*b*) have shown from physically plausible reasoning that the cloud densities are of order $10^2\ \mathrm{cm}^{-3}$, the cloud masses are approximately 10^7–$10^8 M_\odot$, the ambient pressure is inferred to be 10^7–$10^8 M_\odot$ and the filling factor of the cold clouds to be $\sim 10^{-7}$. If there is a hot confining medium it has a mass of $\sim 10^{12} M_\odot$ with a corresponding X-ray luminosity of 10^{46}–$10^{47}\ \mathrm{erg\,s^{-1}}$ that could be seen with the Advanced X-ray Astrophysics Facility. Linewidths here are $10^3\ \mathrm{km\,s^{-1}}$. The colours of the continuum are consistent with high level star formation in a late type galaxy.

6. High Redshift Starburst Galaxy

This object was discovered by Rowan-Robinson *et al.* (1991) during their study of IRAS galaxies. At its redshift of 2·3 it has a luminosity of $\sim 3\times 10^{14} L_\odot$. If it is a starburst it corresponds to 10^9 O5 stars with a total mass of $4\times 10^{10} M_\odot$ with a dust mass of $10^9 M_\odot$. If it is an embedded Seyfert or AGN then the dust mass is even more extreme, $\sim 10^{10} M_\odot$. The mass seen in CO is $\sim 10^9 M_\odot$ corresponding to a mass in molecular hydrogen or order $\sim 10^{13} M_\odot$ (Brown and Vanden Bout 1991). It is quite possible that there are many more of these objects and they may give significant clues to the nature of protogalaxies.

7. Clusters of Galaxies

The intracluster medium is observed to be enriched wherever it has been measured with a mean abundance of the order of the solar metallicity. This material must have been processed through massive stars but the details of the enrichment mechanism are uncertain. The population of E+A galaxies (cf. Gunn 1989) increases dramatically with redshift and reaches 30% at redshifts of order unity. Dramatic low mass star formation rates have been proposed by Fabian and colleagues (cf. Fabian 1988) to explain the fate of the very large mass inflow rates inferred for cooling flows in clusters of galaxies $10^3 M_\odot\,\mathrm{yr}^{-1}$. Of course it is possible that an as yet not understood feedback mechanism will act to inhibit the flow as a result of some process such as star formation.

8. Fuzzy Blue Objects

These objects are seen in the deep CCD surveys (e.g. Tyson and Seitzer 1988) going down to $29\ \mathrm{mag\,arcsec^{-2}}$ in U, B-J and R, and $26\ \mathrm{mag\,arcsec^{-2}}$ in I. The surface density is 3×10^5 per square degree. The colours are consistent with those of blue irregular galaxies. They seem to account for most of the star formation and metal production in the Universe (Cowie *et al.* 1988). Recent surveys done by the Durham group indicate that the mean redshift is very approximately $\sim$0·4. This leads us to the obvious question of why we are making most of the stars and most of the metals in the universe so late, at a redshift of $\sim$0·4!!

9. Starburst Galaxies

Starburst galaxies are the nearby objects most likely to give us the physical insight into the processes of galaxy formation and star formation at high redshift. In particular, the ultra-luminous starburst systems discovered by IRAS have parameters similar to those we have already discussed for the higher redshift objects. They have powerful infrared luminosities $\sim 10^{12} L_\odot$, are usually associated with merging and interacting systems and have inferred star formation rates of $\sim 100 M_\odot\,\mathrm{yr}^{-1}$. The powerful emission in the $2{\cdot}2\,\mu$m line of H_2 can be around $10^9 L_\odot$ and both H_2O and OH megamasers are frequently seen in the nuclei. There are observed outflow rates of $10^2 M_\odot\,\mathrm{yr}^{-1}$ at velocities of order $1000\,\mathrm{km\,s}^{-1}$. There is a possible association with active galaxies and buried quasars and the observed central mass concentration in molecular gas is inferred to be 10^9–$10^{10} M_\odot\,\mathrm{yr}^{-1}$. There are a number of major issues that we could explore in detail here, including the relation of starbursts to active galaxies, galaxy formation, the effects of outflows on the structure of protogalaxies and their relation to quasar absorption lines and finally the nature of the initial mass function in starburst galaxies so that if, as it seems, there are only relatively high mass stars, the underlying reasons why this might be so. We shall address briefly all of these in turn.

10. Starburst Galaxies and Active Galaxies

There is a strong possibility that the massive central starbursts in the class of ultra-luminous IRAS galaxies could be related to buried quasars and AGN since the luminosities are similar and the space distribution is similar. While much work has to be done it should be noted that the observed conditions in these central starbursts of $10^{10} M_\odot$ within 100 pc are quite similar to those originally discussed by Rees and Zel'dovich for the formation of massive black holes. In fact if one takes a cluster of stars of order 10^9–$10^{10} M_\odot$ within 10 pc, and analyses the evolution of the star cluster with a seed black hole at the centre, one finds that the hole grows rapidly from mass loss from giant stars as they evolve and that the central cluster of giants illuminated by the central source could glow in a manner similar to the broad line region clouds. In fact, it seems that they may even be the broad-line clouds themselves.

One interesting test of the starburst AGN hypothesis is to actually image the stars from the starburst in the AGN itself. For example, longer lived A-type spectra should be still seen after the shorter lived AGN phase has passed. The most extreme view here is that of Terlevich who argues that all AGN are powered by starburst-like phenomena and that the black hole model is unnecessary (cf. Terlevich and Melnick 1985).

11. Feedback Effects and Galaxy Formation

The canonical protogalactic model is a massive gas cloud with cold clouds orbiting in a hot confining medium at the virial temperature. The clouds can fall into the nucleus and help power the central AGN or radio source and when they collide star formation can be induced. An interesting question arises when one considers the feedback effect of a massive central starburst or powerful AGN or radio source on the surrounding protogalaxy. The increased ambient pressure can act to lower the Jeans mass and trigger star formation in the clouds, thus enhancing the star formation and galaxy formation process. This would, of course, feed back to increase the energy and momentum input into the surrounding protogalactic nebula. If this energy and momentum input is too great the rest of the protogalaxy could be blown away or, at the very least, expand significantly.

One can then see how a property such as the binding energy of galaxies could be self-regulated and recent calculations of Norman and Ikeuchi (1992) indicate that for a wide range of input luminosities the binding energy of galaxies can be understood in terms of this feedback process.

The outflows from starburst galaxies and their high-redshift galaxy-forming counterparts are very likely to be the origin of the metal absorption lines seen in QSO absorption-line systems. The intergalactic medium and the intra-cluster medium are likely to be enriched in this way also. If formed sufficiently early, cooling shells can be pushed out by these winds to Mpc-type distances.

12. Initial Mass Function

It is often argued that the IMF in starburst galaxies must be truncated since otherwise the available mass in, say, M82 would be used up in a timescale so short that starburst galaxies would be even rarer than actually observed. There may well be a feedback mechanism operating here that keeps a high mass star-forming region in the high mass star-forming mode. One general suggestion is that if there is a general interaction between the magnetic field, the turbulence and the thermal properties such that equipartition approximately holds between all three, then the Jeans mass at constant pressure is proportional to high powers of the temperature, the magnetic field, and the turbulent velocity. If the massive star formation keeps the thermal temperature high and/or stirs the cloud medium sufficiently that the turbulent magnetic energy densities are kept high, then the Jeans masses can possibly continue to be sustained at a high level. The low mass star formation mode is possibly much more quiescent and dominated by the massive star formation mode once it is initiated.

13. Summary

I have presented a number of points from different areas but all are associated with star formation and galaxy formation at high redshift, and with star formation in their low-redshift counterparts, starburst galaxies. These fields are rapidly coming together and, as can be seen from my review, the theory is very far behind the amazingly rapid progress in the observational studies of high-redshift objects. However, much beautiful physics and astrophysics can be learned in this field. It is one of the great intellectual adventures to make sense out of it and in doing so understand the formation of stars, galaxies and structure in the universe.

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