

A Fossil Record of Galaxy Encounters

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The cosmic infrared background (CIRB) is a record of a large fraction of the emission of light by stars and galaxies over time. The bulk of this emission has been resolved by the Infrared Space Observatory camera. The dominant contributors are bright starburst galaxies with redshift $z \sim 0.8$; that is, in the same redshift range as the active galactic nuclei responsible for the bulk of the x-ray background. At the longest wavelengths, sources of redshift $z \geq 2$ tend to dominate the CIRB. It appears that the majority of present-day stars have been formed in dusty starbursts triggered by galaxy-galaxy interactions and the buildup of large-scale structures.

At this very moment, we are receiving light from stars born throughout the lifetime of the Universe. Much of this light is in the form of a diffuse background about 5% as bright as the cosmic microwave background (CMB), a signature of the Big Bang. The Cosmic Background Explorer (COBE) satellite—which measured the residual temperature of the Big Bang as well as the first fluctuations of density when the Universe was only 300,000 years old, the famous seeds of galaxy formation—also permitted the first detection of a diffuse background due to incipient galaxies emitting light at wavelengths of 100 to 1000 μm , the cosmic infrared background (CIRB). The way galaxies evolve from these seeds to present-day galaxies like our own remains a mystery, and we do not yet know with certainty the details of the cosmic bookkeeping, the global evolution of the total energy emitted by stars and galaxies.

The CIRB is a record of a large fraction of the emission of light by stars and galaxies over cosmic history. If galaxies formed through hierarchical merging, as predicted by current models, then distant galaxies may only represent the small precursors of mature galaxies like the Milky Way and galaxies in its neighborhood, and galaxy formation is a continuous process. Hence, the question “How did galaxies form?” may be restated as “When did most of the stars form in galaxies?” And another question arises: “Is there any connection between the development of large-scale structures and star formation within galaxies?” We will see how the information brought about by the CIRB and by the studies attempting to determine its origin sheds some new light on these questions.

The CIRB

The x-ray background discovered in 1962 by Giacconi and his collaborators during a pioneering rocket experiment was first partially resolved into individual sources in the soft energy range by the Roentgen X-ray Satellite (ROSAT) (1), then more deeply and in a wider energy range by the present-day x-ray observatories Chandra and X-ray Multi-Mirror (XMM-Newton) (2–4). Most of the sources are active galactic nuclei (AGNs), supermassive black holes in the center of galaxies that are accreting matter at a high rate. Recent spectroscopic studies of these sources with the Very Large Telescope (VLT) at the European Southern Observatory revealed that they mostly lie at redshifts (z) below 1, with a mean value of $z \sim 0.7$ (4). In the same way, the light emitted by stars, integrated over time, is expected to generate an almost uniform background. In the optical, a lower limit to this background was established by calculating the integrated contribution of galaxies in the deepest field observed, the Hubble Deep Field North (HDFN) (5, 6). The existence of an infrared (IR) background in the 5- to 15- μm wavelength range was also predicted (7) but was attributed to the redshifted ultraviolet (UV) or optical light from very early galaxies.

In 1983, the first all-sky survey at mid-infrared (MIR) and far-infrared (FIR) wavelengths (12 to 100 μm), performed by the Infrared Astronomical Satellite (IRAS), brought about a revolution in our understanding of IR emission from local galaxies. Since the IRAS data were acquired, we know that in the nearby Universe galaxies globally radiate about two-thirds of their light below $\lambda = 5 \mu\text{m}$ (i.e., through direct stellar light); the remainder is absorbed by dust in the interstellar medium and re-emitted at dust temperatures (i.e., in the IR above 5 μm). Moreover, a new class of galaxies was discovered [(8) and references therein] that radiate the bulk of their luminosity in the FIR,

between 5 and 1000 μm . These galaxies, with bolometric luminosities larger than 10^{11} or 10^{12} solar luminosities, are classified as luminous or ultraluminous infrared galaxies (LIRGs or ULIRGs), respectively. They produce only 2% of the bolometric luminosity density in the local Universe, and the starbursts in them are nearly always triggered by galaxy-galaxy interactions. These galaxies must have been more numerous in the past, when the Universe was denser and galaxies richer in gas. Unfortunately, IRAS was not sensitive enough to detect distant objects, but counts of sources at 60 μm in a few deeper fields already showed hints of evolution—that is, an increase in the source density or luminosity in the past.

The extraction of a CIRB from COBE data [(9, 10) and references therein], 34 years after the discovery of the x-ray background, was almost simultaneous with the introduction of new IR and submillimeter observing facilities on the ground [the James Clerk Maxwell Telescope (JCMT) and the Institut de Radioastronomie Millimétrique (IRAM) 30-m telescope] and in space (the Infrared Space Observatory). The CIRB is a measure of the stellar light radiated in the optical and UV (over the history of the Universe) that was absorbed by dust and thermally reradiated in the IR in the 5- to 1000- μm range. The energy density of this background, about 200 times that of the x-ray background and equal to or greater than that of the optical background, came as a surprise. It implies that in the past a larger fraction of starlight was absorbed by dust and that giant starbursts were more common than now. But when? Or at what distance from us? When trying to assess at which epoch the Universe was most active in the IR, the first clue is the shape of the CIRB spectrum. It is reminiscent of the spectral energy distribution of galaxies, as observed by IRAS, exhibiting a hump at a wavelength that for starburst galaxies or for LIRGs is located at $\sim 80 \mu\text{m}$. With a peak intensity of the CIRB around $\lambda \sim 140 \mu\text{m}$ (Fig. 1), and if we assume that the spectral energy density of distant starbursts is similar to that of the local ones, then the sources responsible for the bulk of the CIRB should be located around a redshift of $z \sim 0.8$; that is, we see them as they were about 7 billion years ago, when the Universe was about half as old as it is today (11). A contribution of more distant galaxies at larger wavelengths is suggested by the slope of the CIRB between

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300 and 1000 μm , which is flatter than the spectral energy distribution of a single galaxy at $z \sim 0.8$ (12). Further studies will be needed to identify the sources of the CIRB and to see whether these conjectures are confirmed.

Identification of the Galaxies Responsible for the CIRB

Ideally, one would wish to observe the IR sky with sufficient spatial resolution at $\sim 140 \mu\text{m}$ to pinpoint the individual galaxies producing the peak intensity of the CIRB. Unfortunately, this has not yet been possible. The ISOPHOT detector on board the Infrared Space Observatory (13) did find a population of galaxies emitting at 170 μm , which are one order of magnitude more numerous than expected if the number density and luminosity of IR galaxies had remained constant with time (14). The combined contribution of these galaxies to the CIRB amounts to only $\sim 10\%$ of its value as measured by COBE (14, 15) (Fig. 1), although fluctuation analysis indicates that fainter sources contribut-

ing to a greater extent to the CIRB are also present in the ISOPHOT (16, 17) and IRAS images (18). Identifications are difficult because of the relatively large error box [full width at half maximum (FWHM) of the point spread function (PSF) = 50 arc sec], but it appears that the sources detected are either nearby or rare, extremely bright distant objects.

In the MIR, the gain of sensitivity of the Infrared Space Observatory with respect to IRAS was more than three orders of magnitude. Deep surveys at 15 μm with the camera ISOCAM, also on board the Infrared Space Observatory, yielded an excess of detections of up to a factor of 10 with respect to what would be expected if the relevant galaxy populations had not evolved in the last 10 billion years (19). This constitutes another proof that the IR luminosity of distant galaxies and/or their density were much larger in the past than they are today. Integrating over the ISOCAM source counts, a lower limit to the CIRB at 15 μm was established (11) (Fig. 1).

ISOCAM spectra of local galaxies of all types [(20) and references therein] show a set of features in the MIR (Fig. 1) that are attributed to large molecules, probably polycyclic aromatic hydrocarbons (PAHs) (21) transiently heated to a few hundred kelvin. These features facilitate the detection by ISOCAM of starburst galaxies up to redshifts < 1.3 (Fig. 2). These galaxies invariably have easily identifiable optical counterparts whose IR colors are indistinguishable from those of optically selected galaxies, but they exhibit strong H α emission (22–25). Their redshift distribution peaks around $z \sim 0.7$ to 0.8 (11, 26, 27), as expected if they are responsible for the bulk of the intensity of the CIRB at its peak. Their FIR emission was evaluated using the MIR-FIR relation observed for local galaxies (11, 28). The FIR luminosity of galaxies correlates strongly with the radio continuum (29), as it does with the MIR at least up to $z \sim 1$ (11). It is generally assumed that massive stars are responsible for the UV photons that heat the IR-emitting dust and, when they explode as

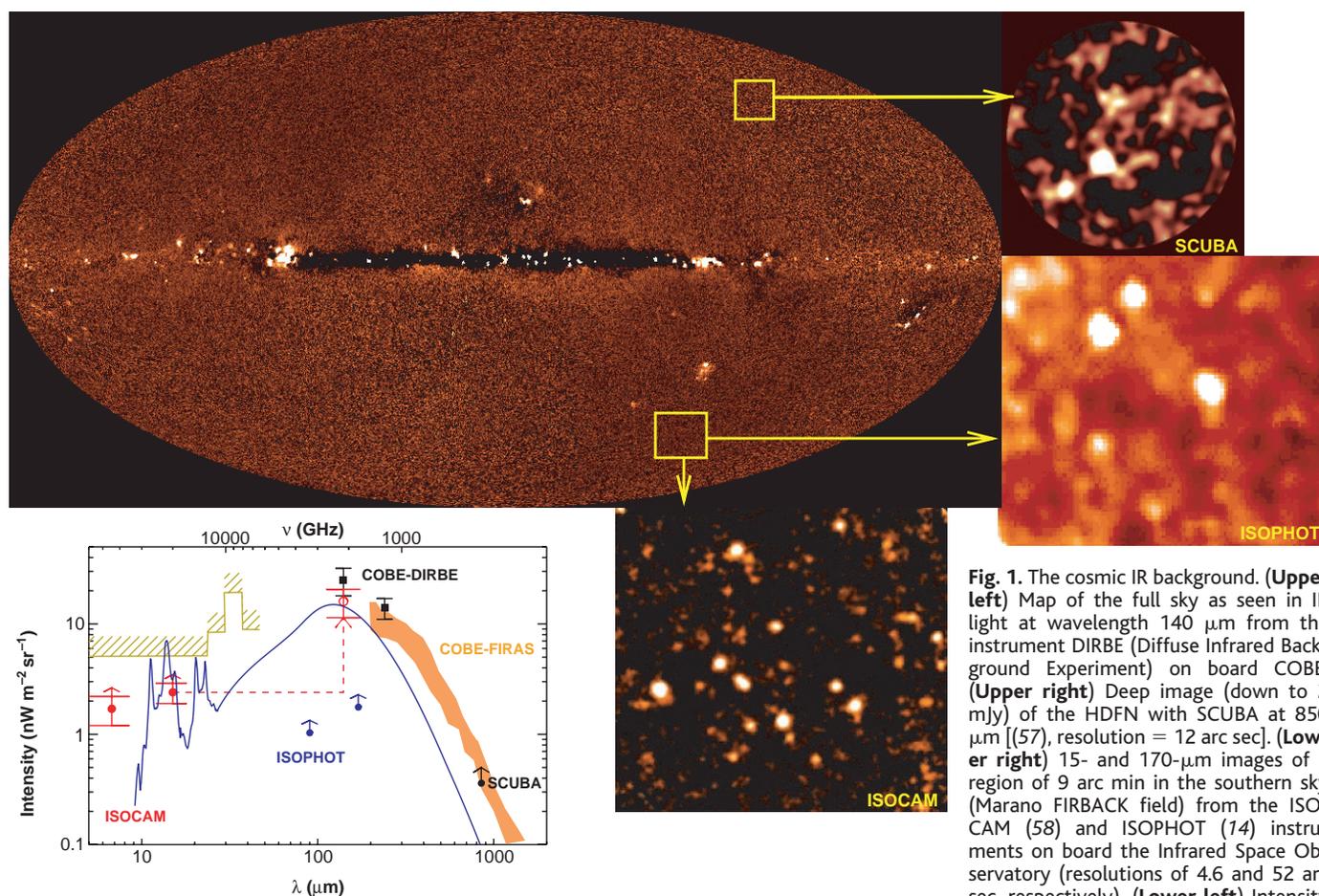


Fig. 1. The cosmic IR background. (Upper left) Map of the full sky as seen in IR light at wavelength 140 μm from the instrument DIRBE (Diffuse Infrared Background Experiment) on board COBE. (Upper right) Deep image (down to 2 mJy) of the HDFN with SCUBA at 850 μm [(57), resolution = 12 arc sec]. (Lower right) 15- and 170- μm images of a region of 9 arc min in the southern sky (Marano FIRBACK field) from the ISOCAM (58) and ISOPHOT (14) instruments on board the Infrared Space Observatory (resolutions of 4.6 and 52 arc sec, respectively). (Lower left) Intensity of the CIRB as a function of wavelength

and frequency. The solid squares with error bars and the orange area give the actual intensity of the CIRB from the DIRBE and FIRAS instruments on board COBE, respectively. The dots with upward arrows (see references in the text) are lower limits set by galaxy counts from ISOCAM (6.75 and 15 μm), ISOPHOT (90 and 170 μm), and SCUBA (850 μm). The lower limit set by ISOCAM at 15 μm was used to compute a lower limit to the CIRB at its peak around 140 μm (dashed arrow) using the MIR-FIR relation (11). The spectral energy density is that of a typical LIRG normalized to the 15- μm point and redshifted to $z = 0.8$. It exhibits broad features attributed to polycyclic aromatic hydrocarbons and peaks at about 80 μm (in the rest frame). The hatched area is an upper limit set by TeV γ -ray photons that annihilate with MIR photons through electron-positron pair production (59–61).

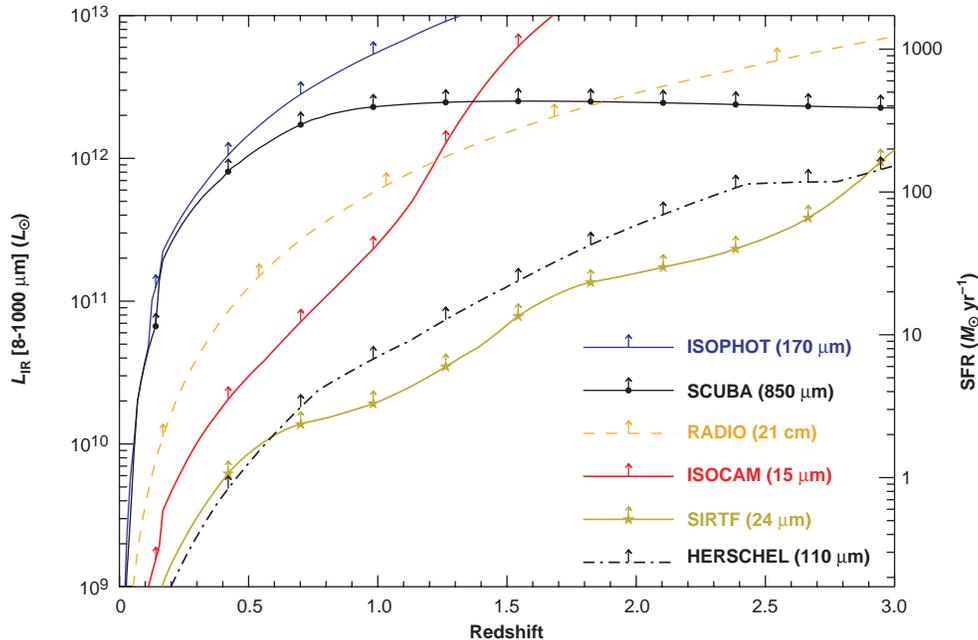


Fig. 2. IR luminosity (left axis) and star formation rate (SFR, right axis) as a function of redshift corresponding to the 5- σ sensitivity (S) limits at different wavelengths (λ) from ISOCAM ($\lambda = 15 \mu\text{m}$, $S = 0.1 \text{ mJy}$) and the VLA in the radio (62) ($\lambda = 21 \text{ cm}$, $S = 40 \mu\text{Jy}$), and to the confusion limits of ISOPHOT ($\lambda = 170 \mu\text{m}$, $S = 120 \text{ mJy}$), of SCUBA ($\lambda = 850 \mu\text{m}$, $S = 2 \text{ mJy}$), and of the future spatial experiment MIPS on board SIRTf (63) ($\lambda = 24 \mu\text{m}$, $S = 22 \mu\text{Jy}$, GOODS Legacy Program) and HERSCHEL-PACS ($\lambda = 110 \mu\text{m}$, $S = 5.1 \text{ mJy}$).

supernovae, for the acceleration of electrons producing the radio continuum. In the future, the Herschel satellite will detect these galaxies directly in the FIR up to $z \sim 3$ (Fig. 2), provided that the spectral energy densities in these distant galaxies with low metallicity and possibly different distributions of grain sizes and abundances of polycyclic aromatic hydrocarbons (30, 31) are not too different from the local ones.

MIR surveys with ISOCAM reach a sensitivity of $\sim 0.1 \text{ mJy}$ at $15 \mu\text{m}$; that is, they are able to detect any galaxy producing more than 20 solar masses of stars per year up to a redshift of $z = 1$, hence over the last 60% of the history of the Universe. Using the MIR-FIR correlations, it is possible to derive a total IR luminosity for each of the galaxies. Integrating the emissions, it was found that the galaxies detected in ISOCAM deep and ultra-deep surveys are responsible for about two-thirds of the peak and integrated intensity of the CIRB. About 75% of these galaxies are LIRGs ($\sim 55\%$) and ULIRGs ($\sim 20\%$) (11); they produce stars with a median rate of about 50 solar masses per year. As a consequence, the density of IR luminosity (per unit of co-moving volume) produced by the IR-bright galaxies at $z \sim 1$ was 70 ± 35 times their present-day luminosity density. This shows that even though LIRGs and ULIRGs play a negligible role in the local Universe, they were important actors in the past and represent a common phase in the evolution of galaxies in general.

An excess of faint galaxies was also detected with the bolometer array SCUBA on the James Clerk Maxwell Telescope down to the confusion limit (2 mJy) (32), accounting for about 20% of the CIRB at $850 \mu\text{m}$ [(33) and references therein]. Deeper surveys using gravitational lensing resolved 60% of the CIRB at $850 \mu\text{m}$ into individual galaxies (33). Unfortunately, the large beam size and the large redshifts favored by this wavelength range have limited the identification of the optical counterparts of the bulk of the sources, and thus the determination of their redshifts, except in rare cases using interferometry (34–36). In a recent study of bright SCUBA galaxies with radio counterparts (37) that allow secure identifications, it was inferred that some of these are indeed powerful ULIRGs located around $z \sim 2$. However, the contribution of sources brighter than 8 mJy to the CIRB is not dominant (38).

Models have been constructed that fit ISOCAM, ISOPHOT, and SCUBA galaxy counts as well as the CIRB itself (12, 26, 39, 40). There is a degeneracy in the parameters assumed, defining the relative roles played by the evolution of galaxies in luminosity and density with time, but all the models share some general conclusions: About 80% of the peak of the CIRB at $140 \mu\text{m}$ is due to galaxies closer than $z = 1.5$; this explains why ISOCAM deep surveys were so efficient in finding the sources of the CIRB. In contrast, about 70% of the intensity of the CIRB at 850

μm is due to galaxies more distant than $z = 1.5$ (28), of which SCUBA is already detecting the brightest members. This also explains why ISOCAM and SCUBA preferentially detect different populations of galaxies but nonetheless obtain perfectly consistent results. Overall, 85% of the integrated light of the CIRB can be attributed to IR luminous galaxies (LIRGs and ULIRGs).

The CIRB and Large-Scale Structure Formation

In the local Universe, nearly all ULIRGs are produced by the merging of two spiral galaxies that will probably result in one intermediate-mass elliptical galaxy (41, 42). About 75% (43) of the local ULIRGs already present a luminosity profile following a $r^{1/4}$ law, typical of early-type galaxies (ellipticals or S0s). The origin of the starburst phase in LIRGs is less evident, but a recent study of local objects (44) shows that it is also linked to galaxy environment ranging from advanced mergers to pairs of spiral galaxies.

In the same vein, less than half of the ISOCAM galaxies exhibit the disturbed morphology typical of merging galaxies, but it is likely that tidal interactions or previous encounters triggered the starbursts, even in the apparently undisturbed ones. The fact that the integrated contribution of bright starbursts to the cosmic star formation history or to the CIRB dominates over that of galaxies forming stars at moderate rates not only implies that most galaxies must have experienced such a phase in their lifetimes but also suggests that each of them went through several such phases (39). In summary, the CIRB appears to be a fossil record of numerous encounters and/or mergers of galaxies, responsible for their briefly prominent IR brightness.

An intriguing corollary is that luminous IR galaxies at redshifts lower than $z \sim 1.3$ may also be responsible for the formation of the majority of present-day stars, as well as of heavy elements, in the local Universe. Indeed, because LIRGs and ULIRGs dominate the cosmic star formation rate history over that estimated on the sole basis of direct UV light (26, 28), they should also dominate in the production of the low-mass stars present today, unless the initial mass function of stars in these starbursts is strongly depleted of low-mass stars. Assuming an updated version of the classical Salpeter initial mass function departing from it below one solar mass (45), the models of Chary and Elbaz (28)—which fit the CIRB and account for ISOCAM and SCUBA results—predict that 60% of present-day stars were born nearer than $z \sim 1.3$, that

is, during the most recent 65% of the age of the Universe (40% below $z \sim 1$, 80% below $z \sim 2$). Because of the dilution of light in an expanding Universe, it is the galaxies at $z \sim 0.8$ that have emitted the bulk of the present-day CIRB. Overall, 80% of the stars born at $z \leq 2$ originated in dusty starbursts (LIRGs and ULIRGs). If these were triggered by galaxy-galaxy interactions, then the environment of galaxies played a major role in the formation of present-day stars, as predicted in hierarchical scenarios of galaxy formation.

About 68% of the field galaxies from a magnitude-limited sample, located in a field 8 arc min wide centered on the HDFN, are located in redshift peaks, whereas all but three of the ISOCAM galaxies in this field (i.e., 94%) belong to these redshift peaks (46, 47), which trace large-scale structures such as sheets, filaments, and groups or clusters of galaxies. A structure located at $z \sim 0.848$ alone contains almost 30% of the ISOCAM galaxies in the field and includes two AGNs detected in the x-rays (Fig. 3). At this

redshift, the 6-arc min extension of the structure corresponds to 3 Mpc proper (i.e., too small to discriminate between a galaxy cluster and a sheet). This hints at a connection between the formation of large-scale structures and of galaxies. This also indicates that large-scale structures may play an important role in the switching on of star formation within galaxies, but additional MIR deep fields with complete spectroscopic redshift surveys are obviously required to test the robustness of this result.

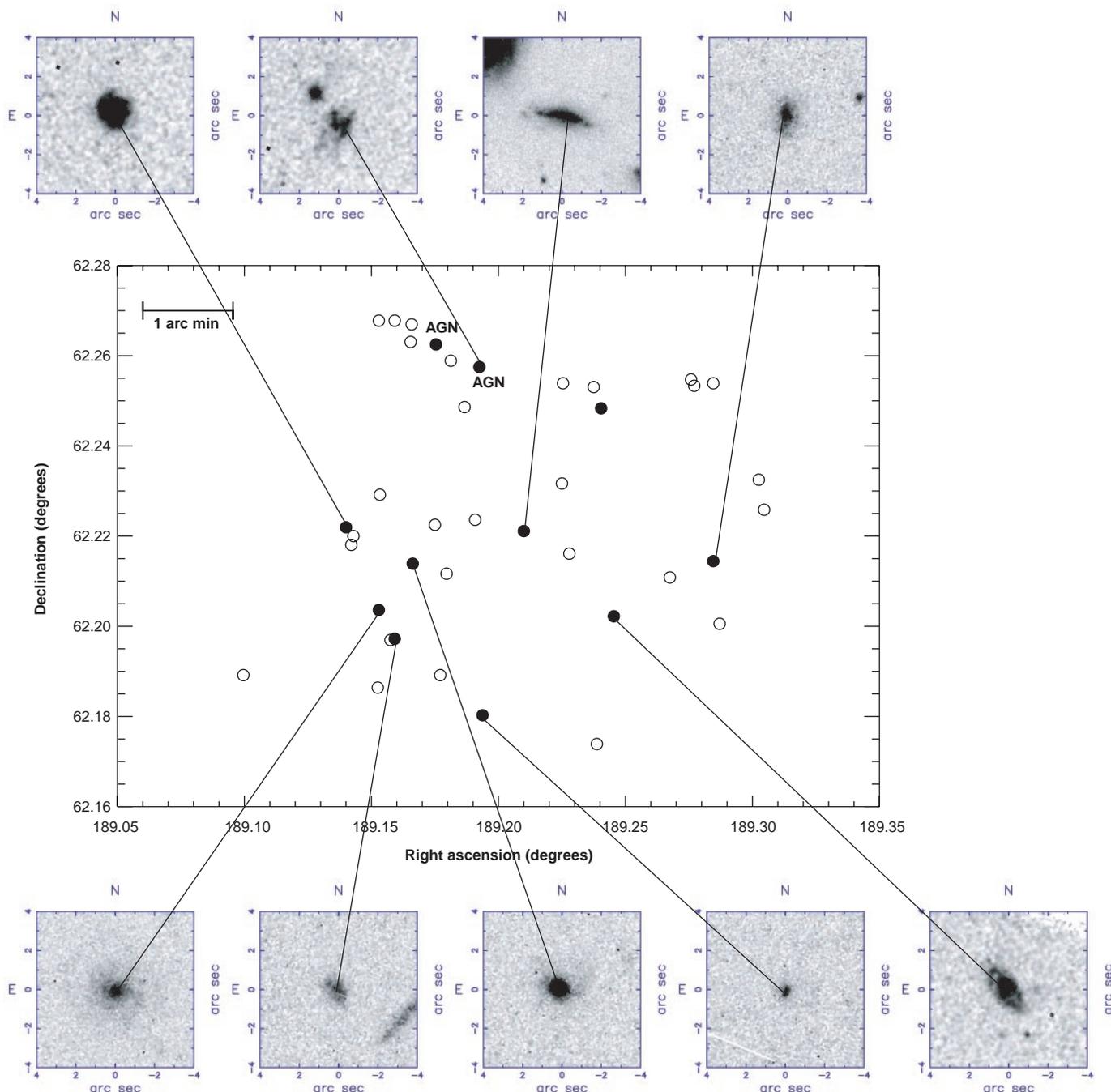


Fig. 3. A large-scale structure at $z = 0.848$ (3 Mpc proper diameter). Empty circles are field galaxies; dark circles are 15- μm ISOCAM galaxies. Postage-stamp HST images of the ISOCAM galaxies are shown when available (from the

DEEP archive database). The positions of two active nuclei (AGNs) are indicated. This is the highest concentration of dusty starbursts ever detected. Each ISOCAM galaxy is forming stars at a rate of about 50 solar masses per year.

REVIEW

What Powers the CIRB: Nucleosynthesis or Accretion onto a Black Hole?

The observed CIRB may originate from light due to nucleosynthesis at the center of stars or active nuclei (i.e., accretion onto a black hole). However, detailed studies of the hard x-ray emission of the ISOCAM galaxies using the deepest x-ray surveys performed with XMM-Newton in the Lockman Hole and the Chandra X-ray Observatory in the HDFN have shown that <20% of their luminosity at 15 μm is due to an active nucleus (48). This result is consistent with the fraction of AGNs within LIRGs and ULIRGs in the local Universe (49, 50). Similarly, the AGNs responsible for the bulk of the x-ray background were found to produce less than 7% of the submillimeter background (51). Nonetheless, the redshift and spatial distribution of ISOCAM galaxies present some striking similarities to x-ray AGNs. Contrary to optically selected AGNs and x-ray quasi-stellar objects, the redshift distribution of the Seyfert-type galaxies responsible for the bulk of the x-ray background also peaks around $z \sim 0.7$ (4). Moreover, x-ray AGNs also exhibit strong clustering, as can be seen in the two deepest images of Chandra, the Chandra Deep Field South at $z = 0.66$ and 0.73 (4) and the Chandra Deep Field North at $z \sim 0.843$ and 1.017 (52). The structure at $z \sim 0.843$ is the same as that mentioned earlier at $z \sim 0.848$ (Fig. 3). Among the 10 x-ray AGNs detected by Chandra, only two are also ISOCAM sources.

This suggests that x-ray AGNs and IR luminous galaxies can act as beacons indicating the regions of growth of large-scale structures. A similar effect was suggested (53) for the more distant population of SCUBA galaxies, although this may instead be an artifact of gravitational lensing (54). The fact that strong starbursts and AGNs exhibit similar spatial distributions suggests that they represent successive phases in the life of galaxies. A recent Chandra discovery (55) may shed new light on this issue: NGC 6240 is a symbiosis between a typical dusty starburst and an x-ray AGN. Recent Chandra observations have revealed that this object encompasses in its center two supermassive black holes probably in the process of merging. NGC 6240 may therefore represent the missing link between dusty starbursts and x-ray AGNs.

Conclusions and Prospects

The recent extraction of a CIRB from the data obtained by the COBE satellite, combined with the results of deep surveys in the IR and submillimeter range, has revealed the importance of star formation in strong starbursts in the history of the Universe. The cosmic star formation rate density was more than one order of magnitude larger about 7 billion years ago ($z = 0.8$) than it is today (28). More than 75% of this evolution

is due to dusty starbursts (LIRGs and ULIRGs) that produced stars at a mean rate of ~ 50 solar masses per year at the earlier epoch. Although the peak and the bulk of the CIRB can be attributed to galaxies at relatively modest redshifts ($z \leq 1.3$), more distant galaxies dominate the emission at submillimeter wavelengths, to which their intrinsic emission is redshifted because of the expansion of the Universe. The brightest of these galaxies, ULIRGs at redshifts $z \geq 2$, are being detected at 850 μm from ground by bolometer arrays at the focus of radio telescopes. The overall importance of ULIRGs seems to have been even greater in those earlier times.

The rapid star formation revealed by IR observations may be connected to large-scale structures. There is a similarity in the redshift distributions, and possibly also the clustering properties, of the bright starburst galaxies and x-ray-selected AGNs. The existence of a link between the triggering of a starburst phase in galaxies and the fueling of a central black hole, already suggested by the study of local ULIRGs discovered by IRAS (56), is supported by this independent evidence.

These findings can also be summarized by noting that galaxies, paradoxically, are sociable and shy at the same time. They are sociable because they brighten up in company. They are shy because during their encounters with other objects, the UV light of their newly formed stars is absorbed by dust and thermally re-emitted in the IR, so that they blush.

The fecundity of this topic promises a bright future for the next generation of IR instruments such as the Space Infrared Telescope Facility (SIRTF), which will be able to bridge the gap between ISOCAM and SCUBA and to study LIRGs and ULIRGs in the $1 \leq z \leq 2$ redshift range. Later, the PACS instrument on the Herschel telescope will resolve the CIRB directly in the FIR, and the James Webb Space Telescope with its MIR camera MIRI will permit detailed studies of the individual sources. The fluctuations of confusion-limited surveys with Herschel will also provide the opportunity to obtain information on FIR sources at redshifts so high that they cannot be detected individually (40). Finally, the combination of all these instruments with the high spatial resolution images and spectra of the Atacama Large Millimeter Array (ALMA) is likely to bring about a new revolution in our understanding of how stars and galaxies form.

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