Spectroscopic analysis reveals that both types of EROs are roughly equally abundant. Hence, about half of the EROs are elliptical galaxies that already have, at $z \sim 1$, a luminosity similar to that of today’s ellipticals, and are at that epoch already dominated by an old stellar population. The other half are galaxies with active star formation which do not show a 4000-Å break but which feature the emission line of [OII] at $\lambda = 3727$ Å, a clear sign of star formation. Further analysis of EROs by means of very deep radio observations confirms the large fraction of galaxies with high star-formation rates. Utilizing the close relation of radio emissivity and FIR luminosity, we find a considerable fraction of EROs to be ULIRGs at $z \sim 1$.

**Spatial Correlations.** EROs are very strongly correlated in space. The interpretation of this strong correlation may be different for the passive ellipticals and for those with active star formation. In the former case the correlation is compatible with a picture in which these EROs are contained in clusters of galaxies or in overdense regions that will collapse to a cluster in the future. The correlation of the EROs featuring active star formation can probably not be explained by cluster membership, but the origin of the correlation may be the same as for the correlation of the LBGs.

The number density of passive EROs, thus of old ellipticals, is surprisingly large compared with expectations from the model of hierarchical structure formation that we will discuss in Sect. 9.6.

### 9.2.3 Submillimeter Sources: A View Through Thick Dust

FIR emission from hot dust is one of the best indicators of star formation. However, observations in this waveband are only possible from space, such as was done with the IRAS and ISO satellites. Dust emission has its maximum at about 100 μm, which is not observable from the ground. At longer wavelengths there are spectral windows where observations through the Earth’s atmosphere are possible, for instance at 450 μm and 850 μm in the submillimeter waveband. However, the observing conditions at these wavelengths are extremely dependent on the amount of water vapor in the atmosphere, so that the observing sites must by dry and at high elevations. In the submillimeter (sub-mm) range, the long wavelength domain of thermal dust radiation can be observed, which is illustrated in Fig. 9.20.

Since about 1998 sub-mm astronomy has experienced an enormous boom, with two instruments having been put into operation: the Submillimeter Common User Bolometer Array (SCUBA), operating at 450 μm and 850 μm, with a field-of-view of 5 arcmin$^2$, and the Max-Planck Millimeter Bolometer (MAMBO), operating at 1300 μm. Both are bolometer arrays which initially had 37 bolometers each, but which since then have been upgraded to a considerably larger number of bolometers. Figure 9.21 shows a 20′ × 17′ MAMBO image of a field in the region of the COSMOS survey.

**The Negative K-Correction of Submillimeter Sources.** The emission of dust at these wavelengths is described by a Rayleigh–Jeans spectrum, modified by an emissivity function that depends on the dust properties (chemical composition, distribution of dust grain sizes); typically, one finds

$$S_{\nu} \propto \nu^{2+\beta} \quad \text{with} \quad \beta \sim 1 \ldots 2.$$
This steep spectrum for frequencies below the peak of the thermal dust emission at $\lambda \sim 100 \, \mu m$ implies a very strong negative K-correction (see Sect. 5.6.1) for wavelengths in the sub-mm domain: at a fixed observed wavelength, the rest-frame wavelength becomes increasingly smaller for sources at higher redshift, and therefore the emissivity is larger. As Fig. 9.22 demonstrates, this spectral behavior causes the effect that the flux in the sub-mm range does not necessarily decrease with redshift. For $z \lesssim 1$, the $1/D^2$-dependence of the flux dominates, so that up to $z \sim 1$ sources at fixed luminosity get fainter with increasing $z$. However, between $z \sim 1$ and $z \sim z_{\text{flat}}$ the sub-mm flux as a function of redshift remains nearly constant or even increases with $z$, where $z_{\text{flat}}$ depends on the dust temperature $T_d$: for $T_d \sim 40 \, K$ and $\lambda \sim 850 \, \mu m$ one finds $z_{\text{flat}} \sim 8$. We therefore have the quite amazing situation that sources appear brighter when they are moved to larger distances. This is caused by the very negative K-correction which more than compensates for the $1/D^2$-decrease of the flux. Only for $z > z_{\text{flat}}$ does the flux begin to rapidly decrease with redshift, since then, due to redshift, the correspond-

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**Fig. 9.21.** The image shows a field of $20' \times 17'$ in the region of the COSMOS survey, observed by the 117-channel MAMBO instrument at the IRAM 30-m telescope on Pico Veleta. Coded in color is the signal-to-noise ratio of the map, where the noise level is about 0.9 mJy per $1''$ beam. About a dozen sources with S/N $\geq 4$ are visible.

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**Fig. 9.22.** Predicted flux from dusty galaxies as a function of redshift. The bolometric luminosity of these galaxies is kept constant. The solid red and the blue dashed curves show the flux at $\lambda = 850 \, \mu m$ and $\lambda = 175 \, \mu m$, respectively. On the right, the index $\beta$ of the dust emissivity is varied, and the temperature of the dust $T_d = 38 \, K$ is kept fixed. On the left, $\beta = 1.5$ is fixed and the temperature is varied. It is remarkable how flat these curves are over a very wide range in redshift, in particular at 850 $\mu m$: this is due to the very strong negative K-correction which derives from the spectral behavior of thermal dust emission, shown in Fig. 9.20.
ing rest-frame frequency is shifted to the far side of the maximum of the dust spectrum (see Fig. 9.20). Hence, a sample of galaxies that is flux-limited in the sub-mm domain should have a very broad z-distribution. The dust temperature is about $T_d \sim 20$ K for low-redshift spirals, and $T_d \sim 40$ K is a typical value for galaxies at higher redshift featuring active star formation. The higher $T_d$, the smaller the sub-mm flux at fixed bolometric luminosity.

Counts of sub-mm sources at high Galactic latitudes have yielded a far higher number density than was predicted by galaxy evolution models. For the density of sources as a function of limiting flux $S$, at wavelength $\lambda = 850$ \(\mu\)m, one obtains

$$N(>S) \simeq 7.9 \times 10^3 \left(\frac{S}{1 \text{ mJy}}\right)^{-1.1} \text{deg}^{-2}. \quad (9.1)$$

The Identification of SCUBA Sources. At first, the optical identification of these sources turned out to be extremely difficult: due to the relatively low angular resolution of SCUBA and MAMBO the positions of sources could only be determined with an accuracy of $\sim 15''$. A large number of faint galaxies can be identified on deep optical images within an error circle of this radius. Furthermore, Fig. 9.22 suggests that these sources have a relatively high redshift, thus they should be very faint in the optical. An additional problem is reddening and extinction by the same dust that is the source of the sub-mm emission.

The identification of SCUBA sources was finally accomplished by means of their radio emission, since about half of the sources selected at sub-mm wavelengths can be identified in very deep radio observations at 1.4 GHz. Since the radio sky is far less crowded than the optical one, and since the VLA achieves an angular resolution of $\sim 1''$ at $\lambda = 20$ cm, the optical identification of the corresponding radio source becomes relatively easy. One example of this identification process is shown in Fig. 9.23. With the accurate radio position of a sub-mm source, the optical identification can then be performed. In most cases, they are very faint optical sources indeed, so that spectroscopic analysis is difficult and very time-consuming. Another method for estimating the redshift results from the spectral energy distribution shown in Fig. 9.20. Since this spectrum seems to be nearly universal, i.e., not varying much among different sources, some kind of photometric redshift can be estimated from the ratio of the fluxes at 1.4 GHz and 850 \(\mu\)m, yielding quite accurate values in many cases.

Until 2004, redshifts had been measured for about 100 sub-mm sources with a median of roughly $\bar{z} \sim 2.5$. In some of these sources an AGN component, which heats the dust, was identified, but in general newly born stars seem to be the prime source of the energetic pho-

![Fig. 9.23. The sub-mm galaxy SMM J09429+4658. The three images on the right have a side length of 30'' each, centered on the center of the error box of the 850 \(\mu\)m observation. The smaller image on left is the difference of two HST images in red and infrared filters, showing the dust disk in the spiral galaxy H1. The second image from the left displays an R-band image, superposed with the contours of the SCUBA 850 \(\mu\)m emission. The second image from the right is an I-band image, superposed with the contours of radio emission at 1.4 GHz, and the right-most panel shows a K-band image. The radio contours show emission from the galaxy H1 ($z = 0.33$), but also weaker emission right at the center of the sub-mm map. In the K-band, a NIR source (H5) is found exactly at this position. It remains unclear which of these two sources is the sub-mm source, but the ratio of sub-mm to 1.4-GHz emission would be atypical if H1 is identified with the sub-mm source.](image-url)