100 kiloohms, one order of magnitude smaller than that of (*6*), and varied only weakly with temperature. They attribute the lower resistivity to better molecule-electrode contacts. Moreover, for two of three samples, proximity-induced superconductivity was observed in their DNA strands.

These results are probably not the last chapter in this saga that is more about contacts than about molecular conduction. If simply making physical contact between a metal and a molecule is not enough to guarantee good electrical contact, what is?

When using scanning probe microscopy, pushing harder on the contact is not the answer. Generally, one of three things happens: The molecule moves under the contact (*8*), it is irreversibly deformed (*9*), or its electronic structure changes as a function of applied stress. In the first case, the tip and the molecule still interact through a tunneling barrier, but the barrier changes depending on which functional group in the molecule is moved closest to the tip by the applied pressure. The current thus changes with increased contact force but not necessarily in a way that reflects the molecular conductivity. In the second case, typical of large molecules with secondary structure, the sample is no longer what we started with and any results are irrelevant to the original molecule. The third case is best known for fullerenes (*10*).

It has long been recognized that to make good electrical contact between a molecule and a conducting substrate, a chemical bond is required. This is usually done with sulfur or selenium bound to gold or silver. Tour has called these connections "molecular alligator clips" (*11*). It is easy to take advantage of this concept at one electrode but much more difficult to do so at two. When a notched gold wire is broken in a solution of benzene-1,4-dithiol (a small molecule with alligator clips at both ends) and the ends are brought together until current flows, this results in a junction formed from a small number of molecules, most of which are chemically bonded to both electrodes (*12*). This break junction geometry gives relatively reproducible results when applied to small rigid molecules but is not easily adapted for longer and more flexible systems. Moreover, the high density of adjacent, singly connected molecules introduces concerns about stray parallel currents.

On page 571 of this issue, Cui *et al.* present a simple method for making good electrical contacts to variable length organic molecules (*13*). They use thiol groups to make well-defined chemical bonds to a gold base electrode and a gold nanoparticle top electrode. Contact to the nanoparticle is made through physical contact with a gold-coated atomic force microscopy tip. The molecule is thus covalently bonded to gold at both ends (see the figure). Isolation of the current to a single molecule is produced by diluting the dithiol functionalized alkane in a sea of monofunctionalized alkanes. Hence, even though the nanoparticle is much larger than the molecule of interest, the number of actual contacts per particle is small and peaks at a single contact per particle.

There are three especially exciting features of this work. The first is the statistical significance of the data. Unlike almost all previous reports, which rely on at most a handful of replications, Cui *et al.*'s report is based on more than 4000 separate measurements. Second, the computed current-voltage curves agree with experiment to within a factor of six, better than any previous work and with no adjustable parameters. Finally, the method can be extended to other nanoparticles and to functional groups other than thiol.

For the first time, it will be possible to systematically study the molecule-contact interface in a reliable and reproducible way. If molecular electronics is all about contacts, the work of Cui *et al.* finally gives us a tool to begin in earnest the study of single-molecule devices.

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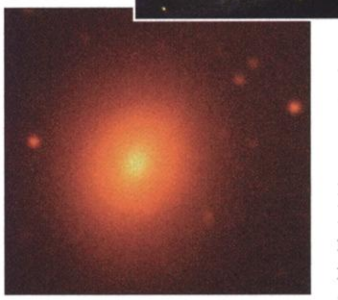
PERSPECTIVES: ASTRONOMY

Toward Resolving the Mystery of Galaxy Formation

Marco Scodeggio

Most visible matter in the universe is organized in galaxies. Yet despite their prominence, little is known about how and when galaxies formed and how they evolved. New evidence is now shedding light on galaxy formation processes in the distant universe, indicating that an answer may be within reach.



Common types of galaxies. These nearby galaxies are easily classified by eye according to their morphological appearance. The elliptical galaxy M32 (**bottom**) is distinctly red, whereas the spiral Whirlpool Galaxy (**top**) is much bluer.

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There are two basic models for galaxy formation. In the monolithic collapse scenario, all galaxies were formed in a single event, through the gravitational collapse of a cloud of primordial gas, very early in the history of the universe (*1*, *2*). In the hierarchical merging scenario, galaxies are gradually assembled through multiple mergers of smaller subgalactic units, a process that continues from the early universe to the current epoch (*3*, *4*).

These differences extend to ideas about galaxy evolution. In the monolithic collapse scenario, galaxies of different morphological types (spirals and ellipticals) are born intrinsically different, whereas in the hierarchical merging scenario, galaxies end up as spirals or ellipticals depending on the details of their merger history. As a result, the first model predicts that the number of galaxies of a given type should be approximately constant at all redshifts (that is, throughout the history of the universe), whereas the second predicts that there number should decrease with increasing redshift (that is, decreasing age).

Attempts to discriminate between the two models focus mostly on elliptical

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galaxies, which are easier to study than spiral ones. Present-epoch ellipticals form a very homogeneous family with very similar intrinsic properties. Compared with the heterogeneous family of spiral galaxies, ellipticals in the local universe have little or no dust, gas, and star formation activity (*5*). Furthermore, they are mostly if not exclusively composed of an old stellar population, about as old as the universe, with very similar relative ages. This fact is responsible for the most distinctive property of ellipticals: their color. Ellipticals are the reddest galaxies in the local universe (*5*).

This last property provides a very powerful tool to search for elliptical galaxies at high redshift. When galaxies are so distant that their images become too small to allow classification on the basis of morphology, candidate ellipticals can be identified by selecting the reddest galaxies in the sample. The intrinsic redness of ellipticals and the further reddening produced by redshift allow color-based selection criteria to be defined that should eliminate all normal spiral galaxies from samples of Extremely Red Objects (EROs).

A high abundance of EROs should indicate the existence of a large number of elliptical galaxies at high redshift, lending support to the monolithic collapse model. In contrast, a low ERO abundance would favor the hierarchical merger scenario. Unfortunately, this seemingly clear-cut picture is complicated by the presence of dust in actively star-forming galaxies. Dust absorbs preferentially short-wavelength photons, making dusty galaxies appear redder than they would otherwise be. ERO samples may thus be contaminated by nonelliptical, dusty galaxies (*6*). If the relative fraction of the latter changes with redshift, this would prevent the use of EROs for discriminating between models of galaxy formation (*7*).

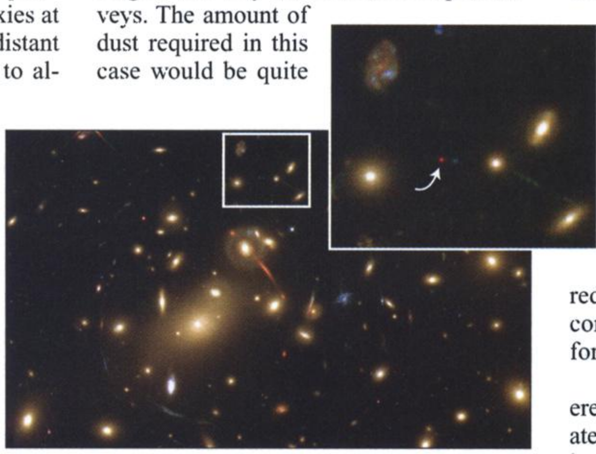
Spectroscopic observations of a large sample of EROs should in principle allow astronomers to distinguish between the two types of galaxies, helping to solve the contamination problem. Such observations are very difficult, however, because EROs are extremely faint at optical wavelengths, where astronomical spectroscopy is carried out most efficiently.

As a result, neither galaxy formation model can be discarded convincingly, although, until recently, the monolithic collapse scenario had to contend with one important, albeit indirect, piece of evidence against it. If elliptical galaxies all formed at high redshift in a single event, for a short period they must have had very strong star formation activity. Simple model calculations indicate that galaxies with so many young and bright stars should be luminous enough to be observable with current telescopes, despite their large distances. But they were never observed.

This lack of detection may indicate that the monolithic collapse model is wrong and that the strong star-forming phase it predicts never took place. Alternatively, dust associated with the intense star formation activity may have obscured these young galaxies so heavily at optical wavelengths that they were invisible to past surveys. The amount of dust required in this case would be quite large, and the combined effect of redshift and dust reddening would make the galaxies appear extremely red. Observations of such Hyper Extremely Red Objects, or HEROs, have now been reported by Totani *et al.* (*8*), who carried out extremely deep infrared observations with the Subaru 8-m telescope of a small area of sky known as the Subaru Deep Field (SDF) (*9*).

HEROs represent a population of very faint galaxies, visible only in the infrared, with colors even redder than those astronomers believe to be characteristic of high-redshift ellipticals. The observed colors are compatible with those of nearby, actively star-forming, dusty galaxies, if those nearby galaxies were seen at high redshift (*8*).

If HEROs are high-redshift, star-forming, dusty galaxies, then all the energy absorbed by the dust at optical and near infrared wavelengths would be re-irradiated in the far infrared (at 60 to 200 μm). They should therefore be bright sources at far infrared and submillimiter (600 to 800 μm) wavelengths. No observations exist at these wavelengths for the SDF. Totani *et al.* (*8*) point out, however, that their measured surface density (*10*) for HEROs is consistent with the surface density of submillimeter sources measured in other recent surveys (*11, 12*). Moreover, these sources often cannot be associated with any galaxy detectable in optical images of the surveyed areas, just as HEROs would be invisible in optical images of the SDF.



Galaxies near and far. This image of the Abell 2218 cluster of galaxies shows many bright nearby galaxies, mostly elliptical ones. In the background (small white rectangle), an Extremely Red Object is barely visible. This ERO can be seen as the small red dot close to the center (arrow) in the enlargement in the top right corner of the figure. Nothing but the color can be measured for this object.

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One last element favors the interpretation of HEROs as dusty galaxies in formation at high redshift: The only other plausible interpretation for their extremely red colors would place them at unrealistically high redshift. The red colors could be a result of neutral hydrogen absorption, instead of dust, but this absorption is highly efficient only at wavelengths shorter than 121.6 nm. This explanation would require HEROs to be at a redshift >10, equivalent to an age of the universe of less than 100 million years, to produce the observed reddening in the infrared. This is generally considered too short a time to have fully formed galaxies in the universe.

It is thus plausible that the newly discovered population of HEROs may be associated with the formation of elliptical galaxies. If this association were confirmed, it would lend strong support to the monolithic collapse model of galaxy formation and would imply that galaxies have existed for the largest part of the history of the universe, rather than being relative newcomers as the merging model would propose.

The observations needed to obtain a complete physical model for HEROs will challenge the capabilities of the newest and largest telescopes in the world to their full extent. But with the discovery of HEROs, the solution of the galaxy formation puzzle appears one step closer.

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