EJECTION OF SMALL COMPACT GALAXIES FROM LARGER GALAXIES

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Abstract. Recent observational evidence is discussed, showing that (1) Galaxies eject matter; (2) Ejection of matter tends to take place in approximately opposite directions; (3) When the ejected matter is in the form of a smaller, companion galaxy, that galaxy tends to have a relatively high surface brightness and small diameter; and (4) Compact companion galaxies generally have higher redshifts than the galaxies from which they were ejected.

A good many years ago Ambartsumian (1958, 1961) said that observational evidence indicated that galaxies could eject luminous matter. Later Vorontsov-Velyaminov (1961) and Hoyle (1965) discussed this hypothesis. I would like to show some new photographs which confirm and further illustrate this process. Figure 1 is a photograph of three hours duration with the 200-in. on IIIa-J plates that goes about one magnitude fainter than the normal limiting magnitude. The object, IC 1182, shows a long straight

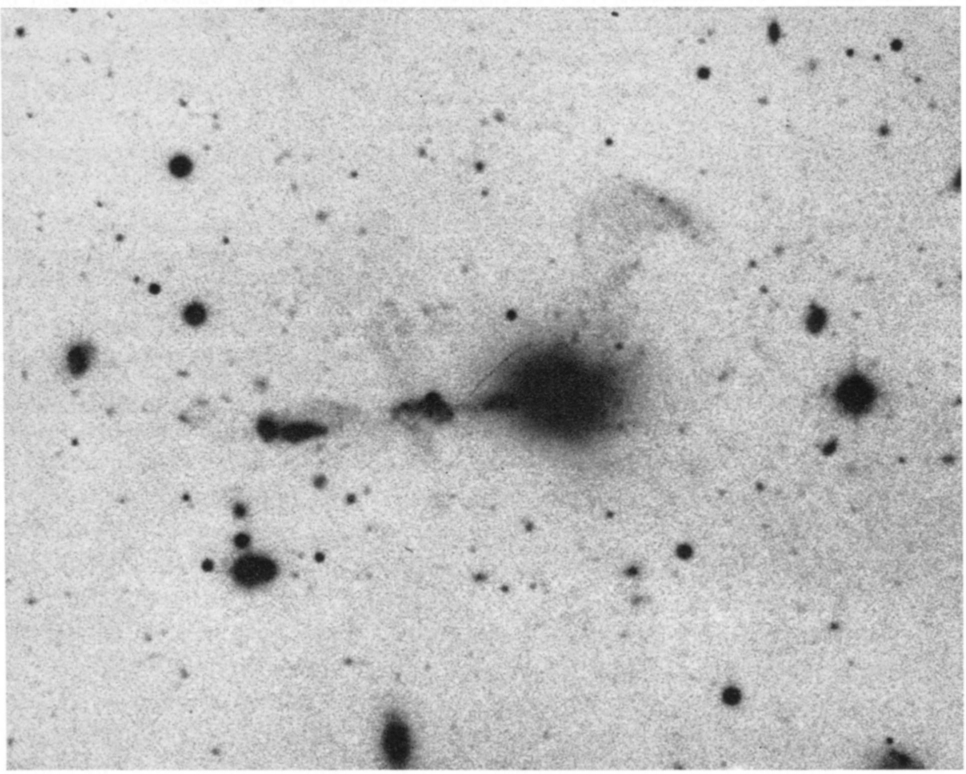

Fig. 1. Galaxy with a jet, IC 1182. Exposure 3 hr on IIIa-J.

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jet with compact, high surface-brightness objects along its length. More diffuse luminous material extends generally in the direction opposite to the jet. The same kind of photographic technique has been used to obtain the deep picture of NGC 3561 shown in Figure 2. There we see the diffuse, luminous matter being ejected northward from the spiral galaxy and the high surface brightness, compact blue object, often

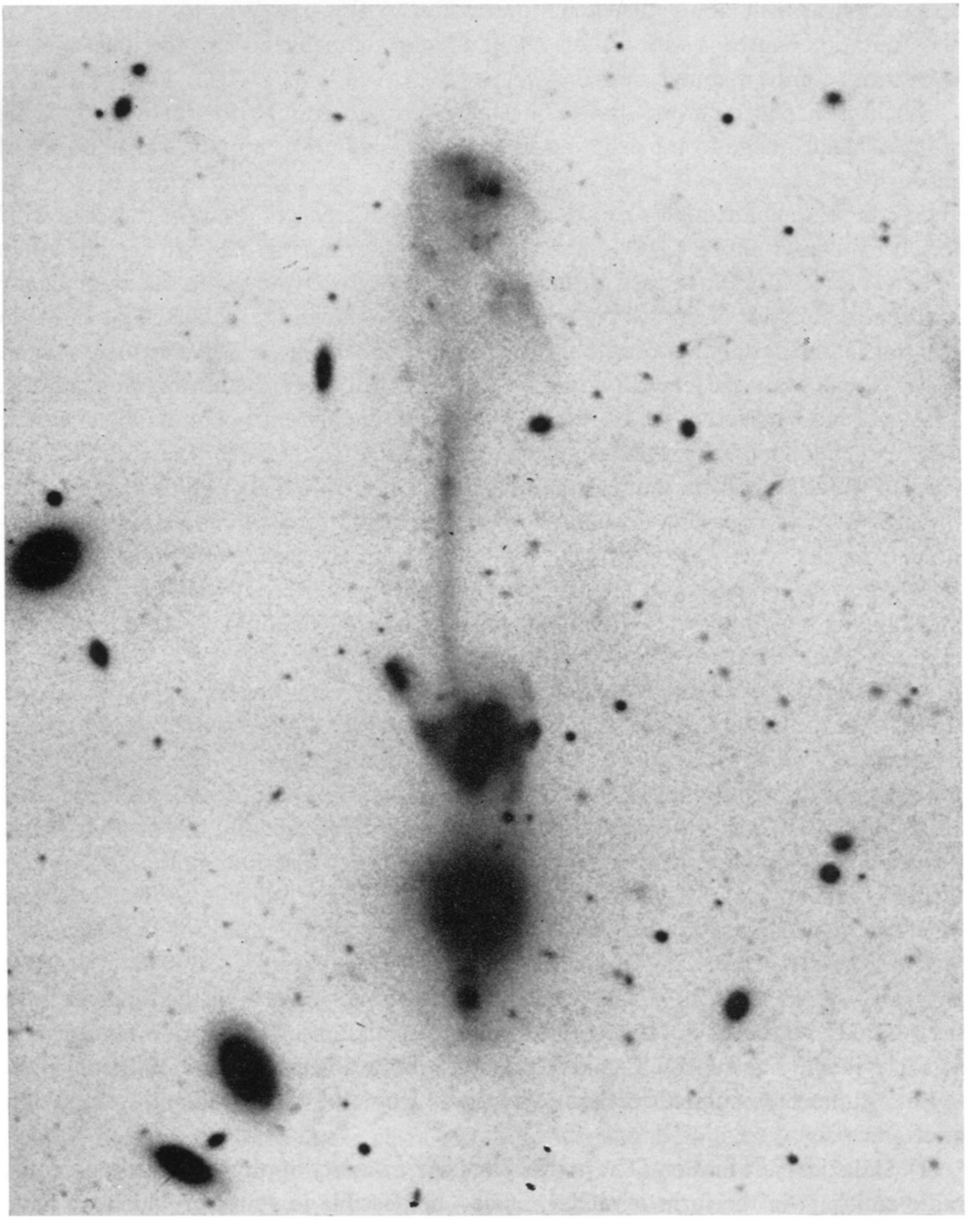

Fig. 2. Galaxy with jets, NGC 3561. Exposure 3 hr on IIIa-J.

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called Ambartsumian's knot, being ejected southward from the elliptical. Zwicky (1958, 1967) has described small stellar appearing condensations along the length of this jet. These objects can be seen very well in the present photograph as well as the extremely narrow jet along which they lie. Spectra of the condensations have been obtained by Zwicky and by Stockton (1969). The strongest feature in the spectrum is generally [O II], λ3727. The [O II] presumably comes from a low density gas but the spectra tell us little about the excitation source for this gas. We must conclude that the excitation source is within these small angular diameter knots and consists of an even more compact source of energy.

Stockton has also shown that of the images bright enough for spectroscopy, the nearest stellar image to the erupting E-galaxy in Figure 2 is a quasi-stellar object of redshift $z = 2.19$.

Of course, the blue, high surface-brightness jet that emerges from the center of M87 has been known since 1918 (Curtis, 1918). Photographs of the jet are shown in Felten *et al.* (1970). In the case of this jet there is apparently no gas in the immediately surrounding region of the galaxy and the compact condensations in the jet show no spectral features, only a strong blue continuum. According to de Vaucouleurs *et al.* (1968), the knots in the jet cannot be photometrically distinguished from point sources. Most astronomers accept the jet in M87 as an ejection phenomenon and long exposure interference filter photographs show an emission line counter jet discovered by Arp (1967b) which extends in a direction opposite to that of the jet. We have, in the case of M87 then, an apparent ejection phenomenon which took place in opposite directions from the center of the galaxy. This ejection involves, in at least one direction, blue luminous bodies, about the brightness of small galaxies ($M_B = -14$ to -13 mag. and fainter) which are very compact, or perhaps even stellar in appearance at the relatively near distance of the Virgo cluster.

Are there other examples that would elucidate the ejection process in galaxies besides the well known examples we have just seen? I would like to show one photograph of a new object which is, I believe, extremely important in enabling us to classify these phenomena observationally. Figure 3 shows a photograph of I Zw 96, an object first catalogued by Zwicky (1964) and later observed spectroscopically by Sargent (1970). Thin filaments emerge from either side of an E-galaxy and four luminous concentrations lie along this line – two on each side of the central galaxy. The brightest object in the filament appears stellar on the direct photograph but the dominant features in its spectrum are galaxy absorption lines K, H and G band, at a redshift within 1% of the redshift of the central galaxy. Fainter objects in the filament have been weakly registered spectroscopically but no emission or absorption features are so far evident. The central E-galaxy manifests both absorption and emission lines.

Four statements summarize my conclusions from the observational evidence on ejection.

(1) Galaxies eject matter. (The matter can be in a variety of physical states; gaseous, radio-emitting, in the form of stellar masses, or possibly in states of which we have no current experience.)

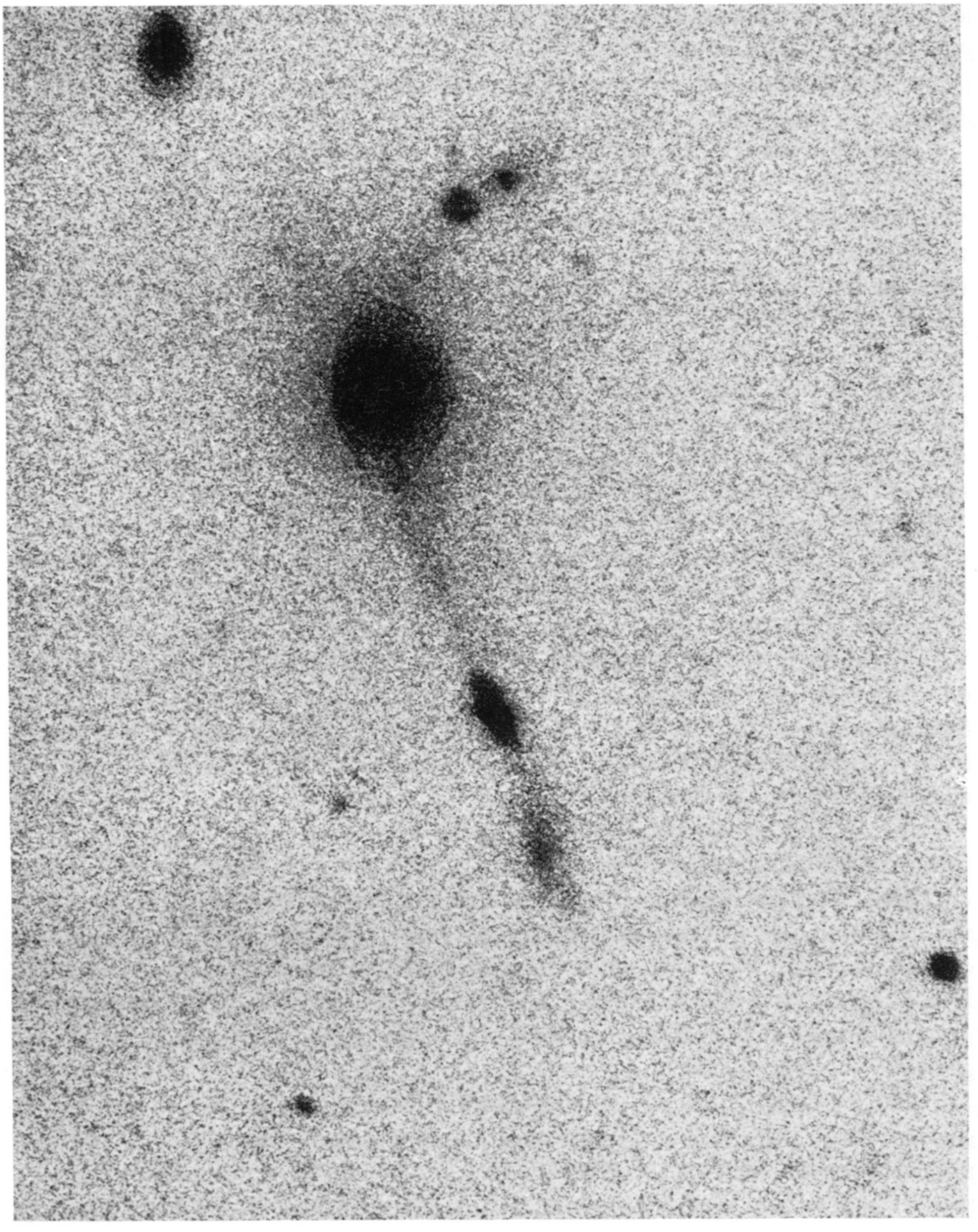

Fig. 3. Galaxy with jets, I Zw 96. Exposure 15 min 103a-J.

(2) Ejection of matter tends to take place in approximately opposite directions. (This is most clearly seen in the cases of radio sources paired across a central galaxy but also can be seen in the cases of ejected luminous matter shown here.)

(3) When the ejected matter is in the form of a smaller, companion galaxy, that galaxy tends to have a relatively high surface brightness and small diameter. (The

corollary to this is that in associated groups of galaxies the more compact galaxies tend to be the fainter.)

(4) Compact companion galaxies generally have higher redshifts than the galaxies from which they were ejected.

Some new evidence can now be given for conclusion (4) which at the same time strengthens the first three conclusions. It should be noted, however, that the observational evidence given by Arp for the ejection of quasi-stellar radio sources from nearby galaxies has previously resulted in exactly these same four conclusions. The evidence on the QSR associations has been published and may be evaluated by any one who wishes to consult the literature (Arp, 1966b; 1967a, 1968a, 1968b, 1969, 1970a, 1970b, 1970c, 1970d; Lynden-Bell *et al.*, 1966; Wagoner, 1967; van der Laan and Bash, 1968). The present evidence, however, is completely independent of the QSR question. We attempt to do a more difficult thing here; we attempt to use galaxies, objects which we presume to understand much better than QSRs, to show that the same set of four conclusions is observationally true.

We start from the result of Holmberg (1969) that nearby spiral galaxies have a statistical excess of small galaxies along their projected minor axes. We adopt Holmberg's model of isotropic ejection of these satellite galaxies with the material in the disk of the central galaxy preventing emergence along the projected major axis. We extend the model by saying that companion galaxies trying to emerge from the disk should be close to, and manifest interaction with, the disk of the ejecting galaxy. Such galaxies are identified as companions on the ends of spiral arms and this process is taken to be the explanation for the whole class of systems known as "spirals with companions on the ends of arms" (Arp, 1970b).

The foregoing results generally confirm the first three rules of ejection. As for rule (4), redshifts of companions in the field of NGC 2403 have been measured (Arp, unpublished results). Statistically, five out of the six nearest companions to NGC 2403 should be physical companions (Holmberg, 1969). All those measured so far have considerably higher redshifts than the main galaxy. Essentially the same situation is true with respect to the companions of NGC 7331 (C. R. Lynds, 1971). An observing program aimed at increasing the redshift data for companions around Holmberg galaxies is currently under way.

In the meantime, however, attention can be confined to those few, well-known galaxies where there is general agreement among astronomers as to which are true physical companions. Table 1 of Arp (1970c) lists three of the nearest systems in which there is a dominant central galaxy and the companions are known with certainty. Six cases of companions on the ends of spiral arms are also listed, since, in these cases, we can also be sure the companions are at the same cosmological distance as the central galaxy. As the histogram, Figure 4, from Arp (1970c) shows, sixteen out of these nineteen companions have positive redshifts with respect to their parent galaxy.

A few, more recently investigated, cases of smaller companions which are known to be at the same distance as parent galaxies may be added to these redshift statistics. The figure in Arp (1970d) shows short and long exposure photographs of 3C 371 and an isodensitometer trace of the long exposure photograph. The radio galaxy 3C 371 is a very compact, optically variable galaxy in a cluster of compact galaxies. The isodensity tracing reveals that the compact companion galaxies on either side of 3C 371 are connected by a faint luminous bridge to the central galaxy. Not only does this

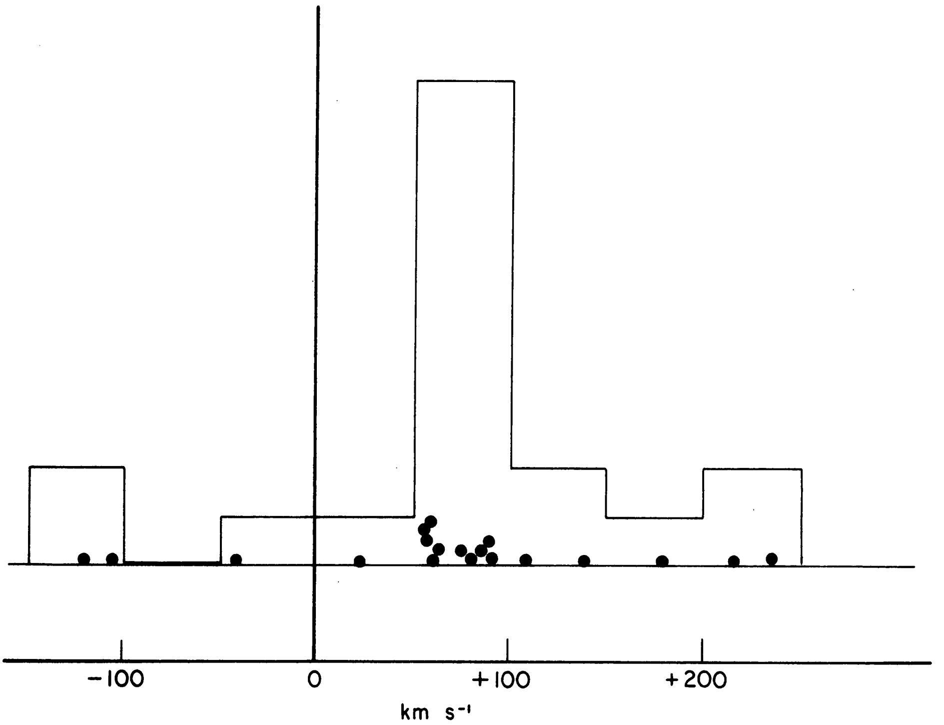

Fig. 4. Distribution of redshifts of companion galaxies measured relative to their central galaxies.

connection strongly confirm the ejection origin of these companions but the one companion bright enough to enable a redshift to be measured, has a 300 km s^{-1} greater redshift than 3C 371. In the beginning of this paper, Figure 3 showed a compact galaxy (one of the condensations in the filament) being ejected from I Zw 96. The redshift of that companion was measured as 200 km s^{-1} greater than the central galaxy.

The positive redshift residuals discussed so far are primarily in the range +50 to +300 km s^{-1}. It is clear that any small galaxies in the area of larger galaxies which had redshift residuals much in excess of this would, under current assumptions, be automatically considered to be unrelated background galaxies. I would like to show two examples, however, where galaxies smaller in apparent size and much higher in redshift appear to be actually connected by luminous filaments to the parent galaxy and therefore make it extremely improbable that these are projected associations of background galaxies.

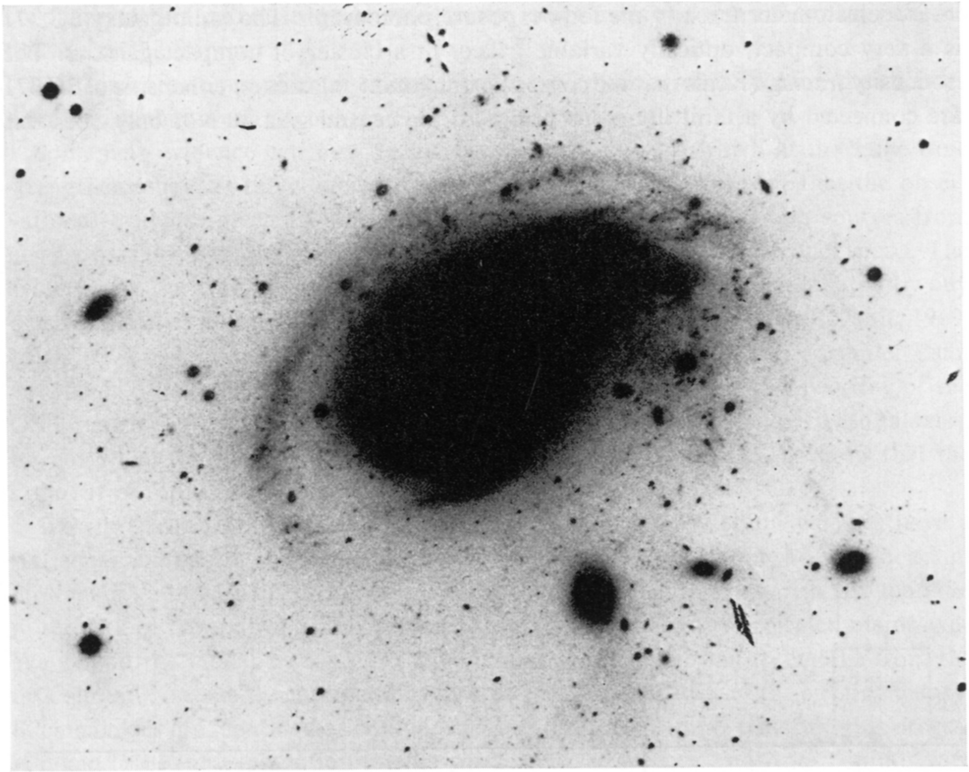

Fig. 5. Galaxy with companions attached by luminous filaments, NGC 772. Exposure 3 hr on IIIa-J.

Figure 5 shows the disturbed Sb spiral NGC 772 (Atlas of Peculiar Galaxies No. 78) (Arp, 1966b, 1970e). The redshifts of NGC 772 and the largest companion are both about 2400 km s^{-1}. The redshifts of the two smaller companions are 19700 to 20200 km s^{-1} respectively. A luminous filament connects the highest redshift companion to the main galaxy. The isodensitometer traces show that the other high redshift companion lies on a luminous protuberance of the outer NGC 772 isophote.

Figure 6 shows the peculiar galaxy NGC 7603. It is No. 92 in the Atlas of Peculiar Galaxies and it is in the same class of peculiar galaxies as the previous example, i.e. spiral galaxies with companions on the ends of arms. In the case of NGC 7603, the main galaxy has a high surface-brightness central region which exhibits strongly the characteristic emission lines of a Seyfert spectrum. Its redshift is 8700 km s^{-1}. The outer regions of the disk are very disturbed and from it leads a single, long arm or filament which terminates at a smaller companion galaxy. The companion galaxy is peculiar in that it has a nearly stellar nucleus with a very low surface-brightness halo surrounding this nucleus. The companion is the only conspicuous galaxy that is in the vicinity of NGC 7603, the single filament leads directly to the companion and terminates exactly at the position of the companion. There can be little doubt that the companion is physically connected to NGC 7603. The spectrum of the companion

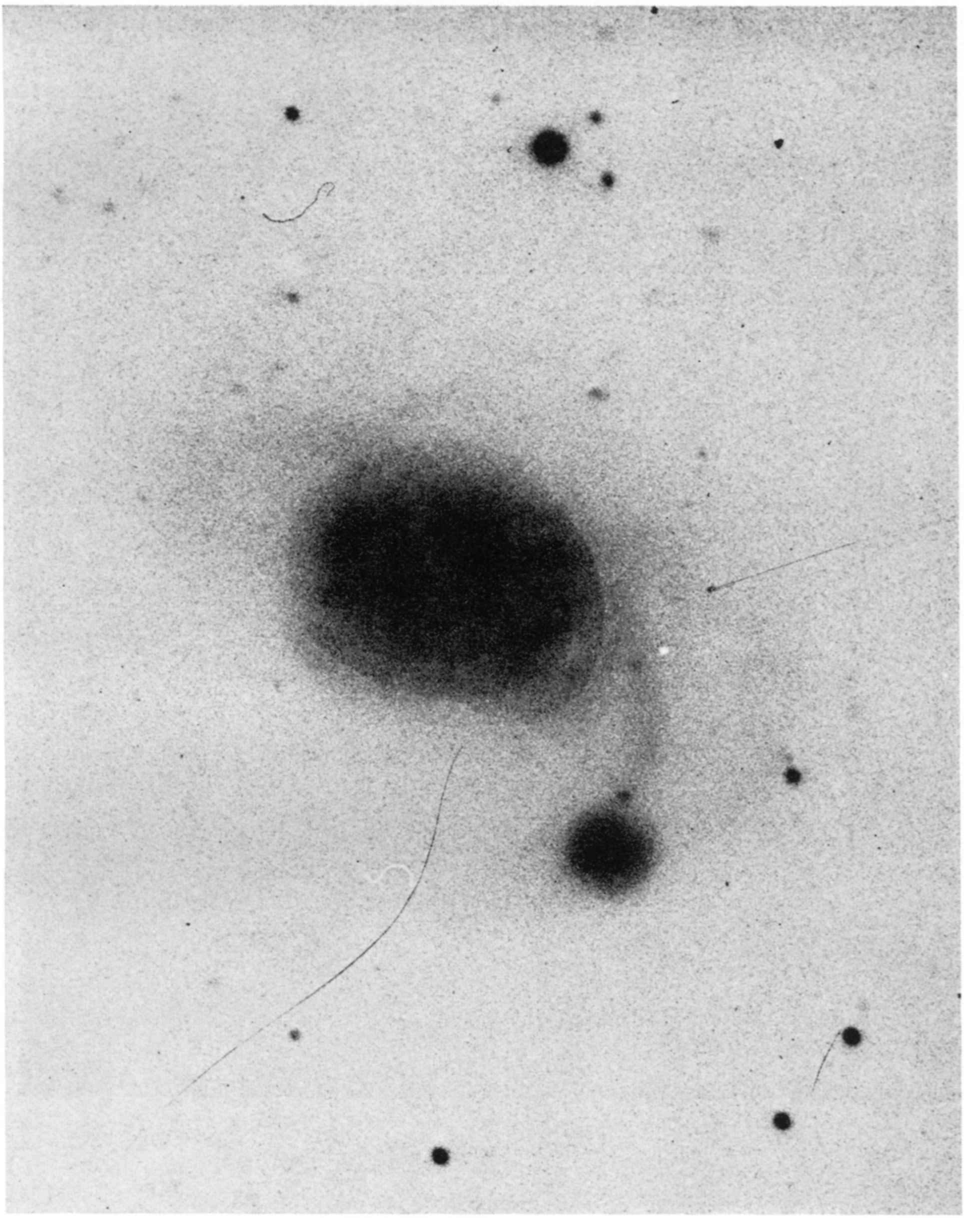

Fig. 6. Galaxy with companion attached by luminous filament, NGC 7603. Exposure 3 hr on IIIa-J.

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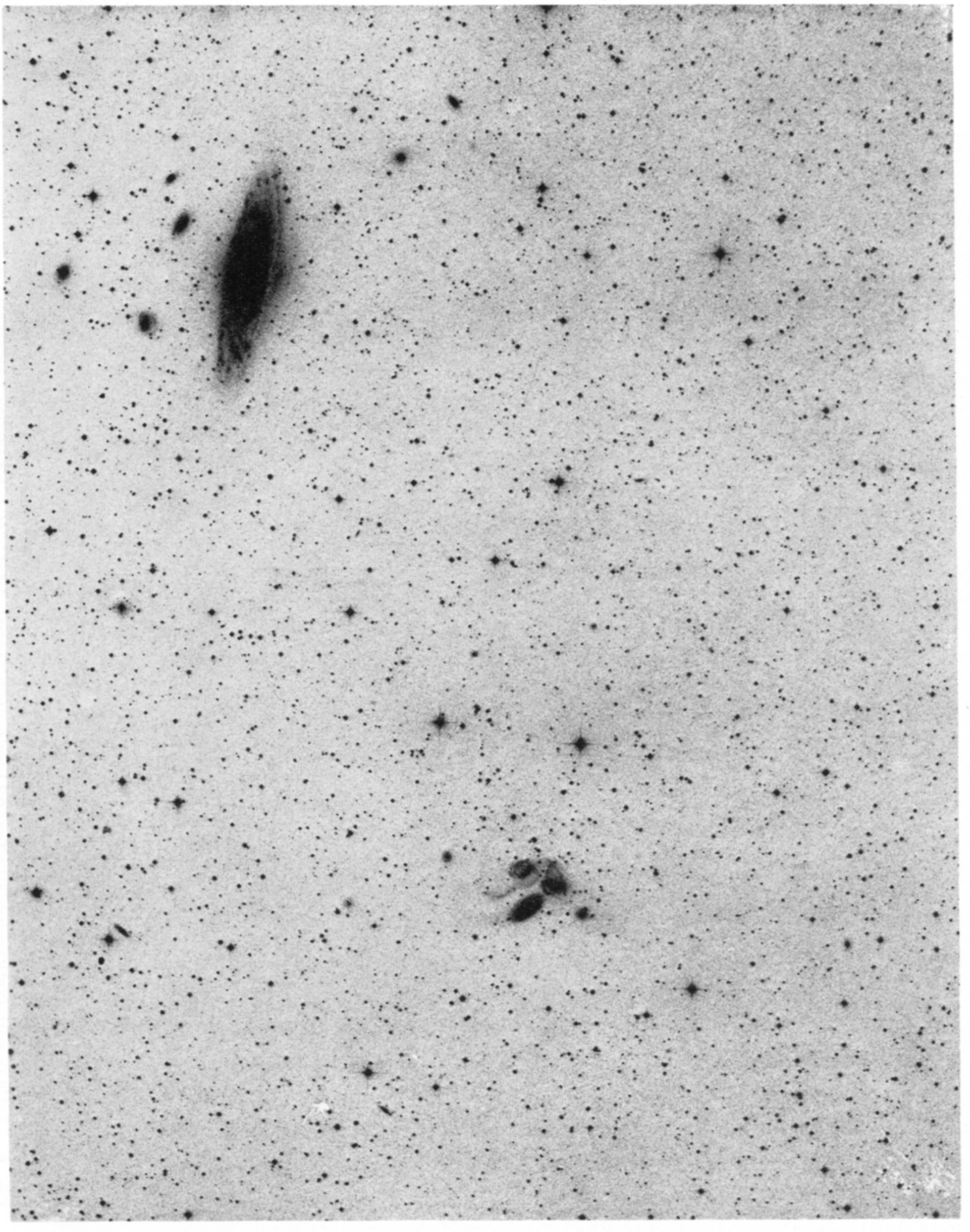

Fig. 7. Field of NGC 7331 and Stephan's Quintet. Superposition print of three 103a-J plates. obtained with 48-in. Schmidt telescope.

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shows, however, only K and H in absorption with a redshift of 16800 km s^{-1}. Accordant redshift measures have been derived from four spectra of the main galaxy and three for the companion.

In most of the cases in which there are apparently associated objects which include one discordant redshift, that discordant redshift is too high. Besides the cases just discussed, an example is IC 4296 with a redshift of 3700 km s^{-1} in the Cen A line of galaxies which line has an average redshift of around 300 km s^{-1} (Arp, 1968c). Another example is the blue compact galaxy in the tight chain VV 172 whose redshift is 37000 km s^{-1} compared to 16000 km s^{-1} for the remainder of the chain (Sargent, 1968; Rees and Silk, 1970).

The single exception to this situation appears at first glance to be Stephan's Quintet. There, four of the group have redshifts from 5700 to 6700 km s^{-1} while the fifth has a redshift of 795 km s^{-1} (Burbidge and Burbidge, 1961; Lynds, 1971). As Figure 7 shows, however, just 30′ northeast of the quintet is the large Sb spiral NGC 7331. It is in appropriate position to have ejected the quintet as companion galaxies and the redshift of NGC 7331 is +794 km s^{-1} (de Vaucouleurs and de Vaucouleurs, 1964), the same as the low redshift member of the quintet. Even more interesting are the companion galaxies immediately around NGC 7331. According to Holmberg (1969) the majority of them must be physical companions but according to Lynds (1971) all of them are at much higher redshift. The three nearest companions to NGC 7331 lie east of the galaxy along its projected minor axis. Their redshifts range from 6300 to 6700 km s^{-1} almost exactly the redshifts of the four members of the quintet which range from 5700 to 6700 km s^{-1}.

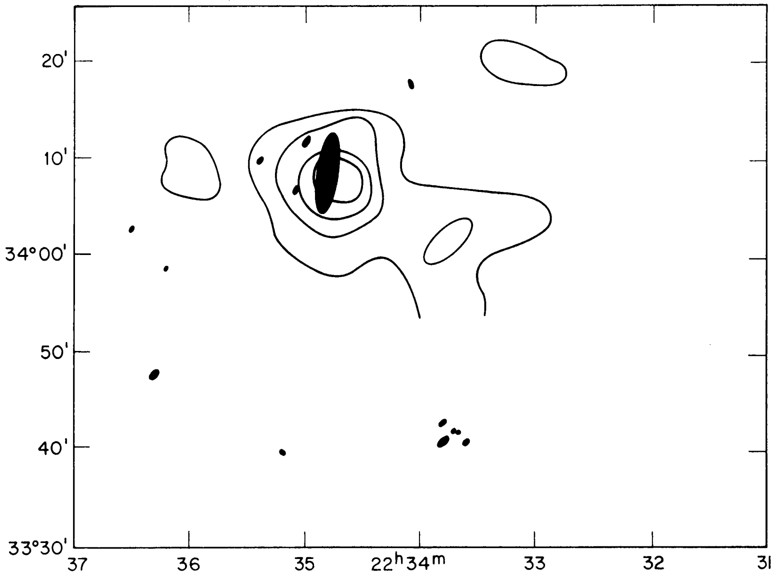

Fig. 8. Radio map of NGC 7331 area. Adopted from measures by De Jong (1966). Radio measures stop just north of Stephan's Quintet.

The conventional interpretation of redshifts in this region of the sky would lead to a model in which two distant, separate groups of galaxies, both at redshifts of about 6400 km s^{-1} happened to be accidentally projected, one right around the nearby spiral NGC 7331 and the other right around its companion NGC 7320 (Stephan's Quintet). This set of coincidences would seem to be so unlikely as to rule out any conclusion other than Holmberg's original one that the galaxies in the vicinity are predominantly physical companions associated with NGC 7331.

To all of the foregoing we may add one final piece of evidence. Figure 8 shows the area around NGC 7331 as radio mapped by De Jong (1966) at 1415 MHz. The area mapped cuts off just north of Stephan's Quintet but as far as these continuum measures go, they show an area of radio emission surrounding NGC 7331 and extending several galaxy diameters away to the west and south, directly toward the position of Stephan's Quintet. Observations by Terzian (1967) at lower frequencies also show extensions from NGC 7331 in somewhat similar directions.

Plates of the region obtained by Arp have been photographically (information) summed and the possible existence of diffuse luminous material along the western minor axis of NGC 7331, opposite the three nearest companions and just in the region of the recorded radio emission, is suspected. More photographic plates are being obtained to check on this feature. It would also be of great importance to extend and check the radio observations in this region.

As the situation stands at the moment, however, it seems to me that the evidence strongly favors NGC 7331 having ejected companion galaxies, more or less in accordance with the four rules set up in this paper, and that most of these companion galaxies have considerably higher redshift than their parent.

Acknowledgement

I would like to thank Roger Lynds for communicating his redshift measures in the NGC 7331 area before publication.

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Discussion of Papers Read by Lynds and Arp

Ozernoy: Have you estimated the kinetic energy of galaxy companions using the differences in radial velocities and luminosities of galaxies?

Arp: My point is that part of the measured redshifts of the companions is intrinsic (non-velocity). Therefore true ejection velocities cannot be estimated easily at present.

Lewis: The apparent correlation of the small redshifts of companion galaxies with respect to the 'parent' galaxy is only obtained through Arp's limitation to a few situations in which he expects the correlation to be true. But any real test of the hypothesis ought to consider the velocity differences between all galaxies for which there is any expectation that they are physically associated. In this category come all of the group data collected by de Vaucouleurs (1965 version of chapter for Vol 9 of Chicago Compendium) and the data on close pairs analyzed by Page (1961). For the purposes of this exercise which was finished before the recent revision of Page's data, the dominant galaxy of a pair or group is the brightest E or S0 if one is present within two magnitudes of the brightest galaxy, otherwise the brightest galaxy is presumed to be the dominant galaxy. This working definition produces several instances in which all other group galaxies have positive or negative velocity offsets, but the apparent symmetry about zero velocity in Figure 1, which shows the distribution of velocity offsets, only broadens the overall distribution, rather than biases it. Only the members of the Local Group are omitted from this figure, which shows the high weight group data (blacked in), the less reliable data from probable group members (hatched) and the data from the less well studied groups (open). Figure 2 shows the distribution of the velocity offsets in Page's double galaxy data, together with Arp's Atlas companions, the Galaxy-LMC system, the NGC 247-253 and 5236-53 systems. The data are very similar to the data obtained from a study of groups, but the more critical conditions for physical association are reflected in the smaller velocity dispersion. In both Figures 1 and 2 there is no more than a 4–5% bias towards redshifts rather than blueshifts. (Figures overleaf.)

Editorial note: Arp's reply to Lewis' remarks has now appeared in *Nature Phys. Sci.* **231**, 103 (1971).

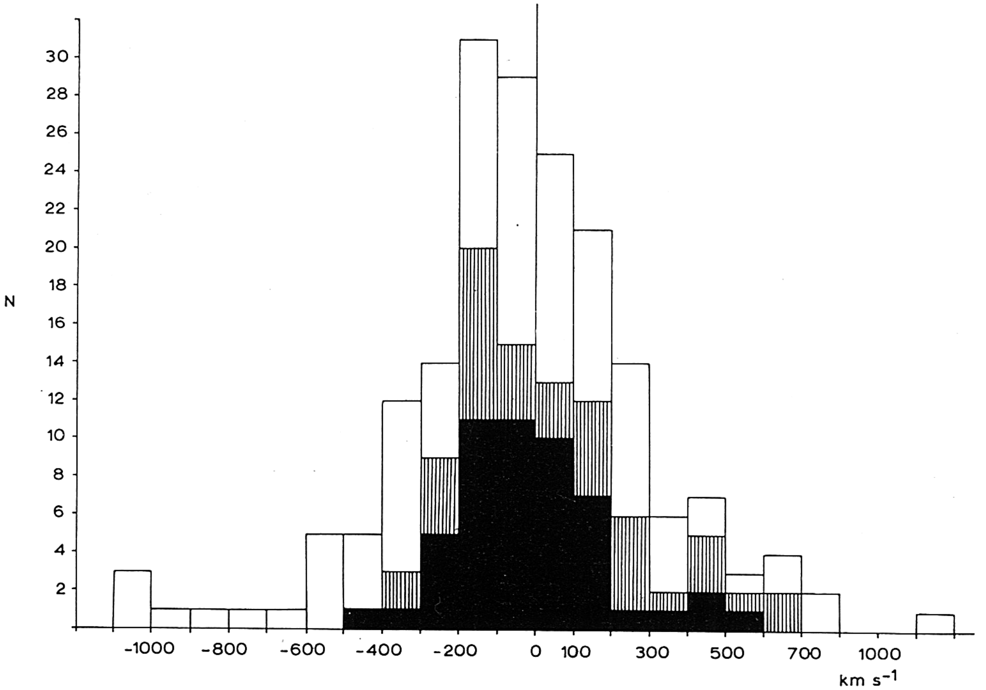

Fig. 1. Illustrating remarks by Lewis on p. 391.

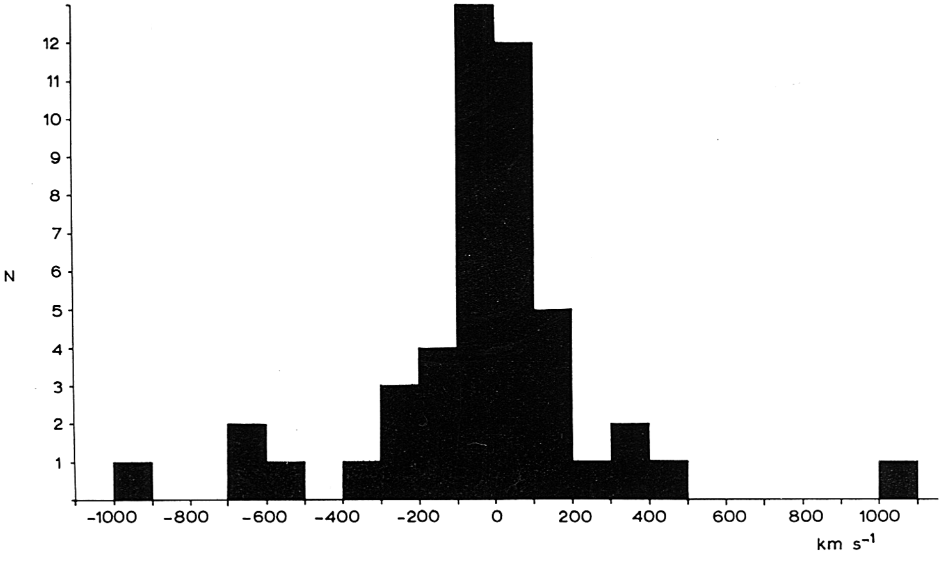

Fig. 2. Illustrating remarks by Lewis on p. 391.

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