RELATIONS BETWEEN THE OPTICAL AND RADIO PROPERTIES
OF EXTRAGALACTIC RADIO SOURCES

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I.   INTRODUCTION

Correlations between the radio and optical properties of radio sources have proved elusive and the main conclusion to be drawn from this is that there is a great variety of objects in the universe that emit nonthermal radiation, so that attempts to use these objects for cosmological purposes can be frustrated unless one can find some way of selecting objects that do have common intrinsic properties. Despite this, the search for relations and correlations is interesting quite apart from cosmology, because such correlations should provide a groundwork for a physical theory or theories of what is really happening in sources of nonthermal radiation.

I want first briefly to discuss radio galaxies, because the problems here are better definable than for the QSOs, for which the basics, even distances and redshifts, and the very obvious heterogeneity of such objects, pose very great problems in their understanding. Then I shall turn to the QSOs and present some new results.

II.   RADIO GALAXIES

A recent catalogue of 3CR sources (Smith, Spinrad, and Smith 1976) lists 137 radio galaxies, and of those for which optical spectroscopic characteristics are given 45 have strong emission lines, 23 have emission lines of moderate strength, 12 have weak emission and 23 have only absorption lines. Thus there appears to be some correlation between a radio source being strong enough to be listed in the 3CR catalogue and the presence in its optical spectrum of emission lines other than just weak [O II] or Hα. On the other hand, when one considers galaxies that are weaker radio sources, the situation changes. Data compiled a year ago (Burbidge 1975) for 222 galaxies

showed that 152 had no strong emission lines in their spectra, while
70 did have strong emission lines. Weaker radio galaxies include
ellipticals and spirals with nuclear emission. Nuclear emission from
spirals becomes quite common at a low level. The E galaxies con-
tribute heavily to the objects that have only absorption lines in their
optical spectra while spirals may have emission lines of weak or
average strength, as well as the fewer cases that have strong emission
lines.

The range of morphological types of radio galaxies have changed
little since the original categorization by Matthews, Morgan, and
Schmidt (1964). There are 15 N systems in the 3CR set of 137
galaxies. It is worth remembering that the original definition by
Morgan (1958) for the N-type galaxies is "systems having small,
brilliant nuclei, superposed on a considerably fainter background."
The "db" or dumbbell galaxies, i.e. double ellipticals in a common
stellar envelope, have however been found to be much rarer than
appeared in the Matthews, Morgan, and Schmidt list. The giant E or
D galaxies, very often the brightest members of clusters of galaxies,
still predominate.

Several papers in this symposium have discussed correlations
between radio spectral index and luminosity of radio galaxies, and
the paper by Osterbrock describes in detail optical spectrophotometric
results for a number of radio galaxies. I think one can say that there
is a tendency for a compact radio or optical object to possess strong
emission lines in its optical spectrum. There is especially a tendency
for objects with complex radio spectra to be associated with compact
optical objects; N systems certainly fall into this category. However,
there is one notable exception to the statement that compactness goes
with the presence of strong emission lines, and that is the BL Lac
objects. I will discuss these in Section V of this paper.

III.   QSOs -- GENERAL CONSIDERATIONS

One of the important questions which one would like to be able to
answer is "What is the relation between radio-emitting and radio-
quiet QSOs?" QSOs were first discovered as radio sources, but
apparently they are far outnumbered in the sky by the radio-quiet
objects. We have estimates from Sandage and Luyten (1967) of the
number of radio-quiet QSOs per square degree down to a magnitude
limit of 19.7; the number usually adopted is 5 per square degree.
This number may, however, need revision; it may not be simply
extendable to fainter objects; it may even not be constant across the
sky. These are all questions which need to be looked into and new

programs for finding radio-quiet QSOs from objective prism spectra, both by M. Smith and P. Osmer in the southern hemisphere and by A. A. Hoag in the northern hemisphere, are expected to throw some light on this question soon. Harding E. Smith, A. A. Hoag and I have been observing some of the objects in the region of sky covered by the Hercules cluster of galaxies; these objects were discovered by A. A. Hoag in his objective "grism" study using the 4-meter telescope at Kitt Peak. The preliminary results are very interesting, since there appear to be a large number of objects -- 16 candidate QSOs in the first field of approximately one square degree which was searched, of which 8 have been confirmed, and something like 11 candidates in the second field nearby but off the Hercules cluster. This search method is subject to observational selection in that objects of high redshift will predominantly be found, since they show $Ly\alpha$ emission which is the strongest line. We need to extend such research to objects of lower redshift. The old way of finding radio-quiet QSOs, by looking for objects with UV excess, may still be the best way of finding low-redshift objects, and, since this method may discriminate against high-redshift objects, a combination of the two may cover the whole redshift range.

Let me now turn to some comments on the models for QSOs in which photoionization is the input that controls the region giving rise to the emission lines. One important question is what happens at the Lyman limit; this can be observed in objects at high redshift. Among such high-z objects there is a range from those in which there is no discernible discontinuity at the Lyman limit to those in which there is a very heavy and almost complete absorption there so that very little radiation is emitted immediately shortward of 912 Å. This emphasizes once again the gross differences that exist from one object to another. The emission-line spectrum in any one object also clearly indicates that there are inhomogeneities of temperature and density in the region producing the emission lines. In addition, the line-emitting material must be concentrated in blobs which do not fully cover the continuum source, for the following reason. The ratio of $Ly\alpha$ to $Ly\beta$ emission in those objects of sufficiently high redshift to show $Ly\beta$ is such that $Ly\alpha$ is very strong and $Ly\beta$ is weak or almost absent. This can be interpreted as being due to an optically thick line-emitting region. Every $Ly\alpha$ photon which is produced throughout the emission region escapes after many scatterings. But $Ly\beta$ photons are degraded into $Ly\alpha$ + $H\alpha$ and thus the $Ly\beta$ that one sees comes only from a thin skin of the emitting region. But optically thick material must not fully cover the continuum source because it would then cause a very large absorption at the Lyman limit, and as already noted there are objects in which this is not the case. Thus the line-emitting

material may be distributed in blobs which partially cover the con-
tinuum source. Another possible model is one in which the emitting
gas does not have spherical symmetry about the central object.
Indeed, this might well be the case if the central object is a strongly
gravitating collapsed mass in which there was initial angular momen-
tum.

In connection with models, before describing some specific
results that I would like to present, I want to mention the absorption-
line spectra that appear at many redshifts in objects of high z. It
appears promising to explain these by means of radiation-pressure-
driven outflow of gas, which can be accelerated to high velocity and
is then subject to instabilities so that it breaks up into small filaments.
A new consideration is that the outflow might also be driven by cosmic
ray pressure. Some work along these lines is being done at the Max
Planck Institute for Astrophysics in Munich, in collaboration with
G. Burbidge.

Another question to consider is whether or not the apparent
abrupt drop in the redshift distribution at $z \gtrsim 2.3$ is real. It is not
clear to what extent this may be due to observational selection. If
objects are identified with radio sources on the basis of their having
a UV-excess or appearing as blue stellar objects on the Palomar
Atlas, there might very well be such a selection against high-z QSOs,
because some of those objects have heavy absorption beyond their
Lyman limit and some have a multitude of absorption lines shortward
of Lyα, so they will not appear strong in the ultraviolet and therefore
may well be missed. The new searches designed to pick up high-
redshift quasars should provide new statistics here.

IV. QSOs -- OBSERVATIONAL RESULTS

Before describing these, let me outline ways in which optical
astronomers can work together with radio astronomers:

1. One can work with a well-defined radio sample and get
   optical observations of as many objects as possible at low
   signal to noise.

2. One can work on particular, limited, radio samples, for
   example, those selected by means of their radio spectral
   properties.

3. One can work on individual objects which have been selected
   either from their radio or optical properties as being of
   particular interest.

Programs underway include examples of all three.

1.   Optical Survey of Molonglo Radio Sources

Identifications and optical observations of sources in the MC2 and MC3 catalogues have been made by a group including C. Hazard, H. Murdoch, J. Baldwin, H. E. Smith, E. J. Wampler, and myself. The optical observations were made at Lick Observatory with the 3-m telescope and the Wampler-Robinson image dissector scanning spectrograph. The +11° and +16° of the MC2/3 from R. A. 11 1/2 to 17 h have been fairly well covered. There are 65 candidate QSO identifications, of which 42 have had reliable spectroscopic observations. Of the BSOs, 38 proved to be QSOs and 4 were galactic stars. This indicates a high degree of reliability, around 90%, for the identifications. Work in other regions of the sky covered by the MC2 and MC3 catalogue is less advanced, but a similar ratio of reliability of identification has been found in the R. A. 20 to 24 h region. For the whole two strips, we have so far 57 confirmed QSOs and 2 BL Lac objects. In addition to BSOs, several red stellar objects which might be identifications of the radio sources were observed, in an attempt to be sure not to discriminate against high-z QSOs. Of these, 9 proved to be galactic stars and 1 was one of the 2 BL Lac objects found. This strongly suggests that in this sample there do not exist a large number of very high redshift red or neutral color objects. There are 8 objects which have continuous spectra, i. e. our observations have sufficiently high signal to noise to indicate that these are not galactic stars and may well be candidate BL Lac objects.

Of the 600 known QSOs, this Molonglo sample comprises 10%. It is of interest to consider properties such as the mean redshift and distribution of redshift. We find $\langle z \rangle = 1.162$, which is very similar to $\langle z \rangle$ found for the 4C QSOs. The distribution in redshift is also similar to that found from previous samples and again indicates a paucity of objects with redshift $z > 2.2$. It is interesting that there is a suggestion of a peak at a redshift of about 0.8 to 0.9, which does not appear in the distribution for the total 600 known QSOs. There are of course not enough observations so far to say whether this is a real peak.

We have looked into the question whether there is a systematic variation of redshift around the sky at a level corresponding to 10% in velocity or variation in numbers of QSOs around the sky. There may be some indications of patchiness, but it is too early to say anything definite one way or the other.

With this good sample of objects, it is interesting to look for a correlation of the continuum spectral index with important emission lines such as Lyα, C IV, Mg II, and Hβ. In a preliminary search we found no correlation, although the simple photoionization model would predict a dependence of equivalent width of emission lines upon the shape of the optical continuum. I believe the only conclusion to be drawn from this is again that the QSOs comprise objects which have a very wide range of physical conditions.

I want to turn now to very preliminary results by the same group of observers on sources in the Molonglo faint survey, MC5, using identifications by D. Jauncey, C. Hazard and H. Murdoch. H. E. Smith and I obtained spectra of some half dozen objects and found the first four to be high-z QSOs:

Object	Redshift	Object	Redshift
0758+120	2.66	0830+115	2.97
0824+110	2.29	0938+119	3.19

Again, a wide range of physical conditions must be present in these four objects. 0938+119 and 0830+115 are like the Ohio cm-excess objects OQ 172 and OH 471 which have flat or peaked radio spectra. In 0938+119 there is a clear discontinuity near the Lyman limit but as in OH 471 this does not occur at the wavelength corresponding to z_{em} but at a shorter wavelength, and it is probably produced by a multitude of absorption lines. 0830+115, like OQ 172, does not have a Lyman discontinuity but has hundreds of narrow absorption lines shortward of Lyα emission. It is interesting to note that none of the 5 QSOs with highest z (OQ 172, OH 471, 0938+119, 0830+115, and 4C 5.34) have complete absorption in the Lyman continuum continuum at a wavelength corresponding to that given by their emission-line redshift system. Yet the absence of Lyβ emission again indicates that the regions producing the emission lines is optically thick as discussed above.

Concerning the emission-line strength in these high-z objects, the ratio C IV to Lyα is larger than the "normal" value of 1/4. O VI is present in 0830+115 and 0938+119.

2.   Red QSOs and BL Lac Objects

I want now to turn to consideration of two groups of objects, those which I shall call the red QSOs, and the BL Lac objects. There are six 3C objects which have been identified as QSOs, but which are distinctly red in color:

3C 68.1	3C 154	3C 418
3C 108	3C 212	3C 422

Boksenberg showed that 3C 68.1 has a very steep slope in its optical continuum with $\alpha \approx 6$. These objects are quite difficult to observe because they tend to be faint. Harding E. Smith has studied 3C 418. It has a $m_V \approx 21.0$, and a continuum slope in the optical region $\alpha = 4.3$. This value of 4.3 may possibly be reduced to about 4 if one corrects for an average extinction in our own Galaxy. The redshift z = 1.687. It has Mg II, C III], and C IV emission lines of normal strength. That these objects are fairly rare is indicated by the fact that only these six have emerged in the approximately 50 QSOs in the 3C catalogue. However, it must be remembered that due to their red color and their faintness they may have been discriminated against in identification and their actual relative numbers may be higher than indicated by these results.

The BL Lac objects are extremely compact in both their radio and optical radiating regions, as is indicated by the characteristic features by which one defines BL Lac objects -- that they show very strong variability on very short time scales, and a high degree of polarization which itself is variable in both extent and angle. What distinguishes the BL Lac objects from the optically violent variable QSOs is the lack of reasonably strong emission lines in them. They were first categorized as having no emission lines at all, but some, when high S/N observations were obtained, have been shown to have weak emission lines. The lack of strong emission lines can be due to two causes -- either a lack of ionizing radiation, or a lack of gas to be ionized. The former is suggested by the fact that the BL Lac objects resemble the red QSOs in having steep spectral indices and they appear neutral or reddish in color on the Sky Survey plates. One may note that there is plenty of gas seen in the spectrum of one very interesting BL Lac object, viz. AO 0235+164. This absorbing gas was shown by Burbidge et al. (1976) and Rieke et al. (1976) to possess two redshifts, z = 0.524 and 0.851; it is the first object found to have two absorption-line redshifts less than z = 1.

If one attempts to explain the weakness of the emission lines in BL Lac objects as being due to steepness of the optical continuum, however, it is interesting to note that the C IV line is quite strong in the red QSO 3C 418, and it requires very short-λ radiation to produce C^{+++}. This argues for there being a considerable flux of either high-energy particles or shock waves to ionize the gas, or else that the continuum is complex and increases again at shorter wavelengths than can be observed from the ground.

V.   THE RADIO SOURCE 3C 303

3C 303 has a very interesting history and is an example of my
third category of cooperation between radio and optical observers.
Wyndham (1966) identified the source as an N-type galaxy, but noted
that there was a blue stellar object about 20'' away which might also
be the source. Sandage (1973) measured z = 0.141 for the galaxy,
from strong emission lines. Later observations with higher reso-
lution indicated that the radio source was complex and encompassed
both the galaxy and the BSO. Optical observations using an electrono-
graphic camera were made by Wlérick and Lelièvre (1975), who noted
that there was actually a group of three objects within a few seconds
of arc which all had a strong UV excess. These lay within the complex
radio source and appeared to be connected with it. The brightest of
the group of UV excess objects was quite faint, being around 20th
magnitude, and at the time my attention was drawn to 3C 303, by P.
Véron, it was not possible to observe with a conventional spectrograph
because of sky background. It was necessary to wait until the Wampler-
Robinson image dissector scanner was available on the Lick 3-m
telescope, so that sky subtraction could be performed.

Kronberg has made detailed radio observations at NRAO and
Westbork and has mapped the structure of the radio source and has
noted that the optical object, the N galaxy and the group of UV-excess
objects lie, as described by the French workers earlier, within the
radio source and seem to be associated with its strongest isophotes.
One of the fainter objects lies right on the compact center of the
western component of the radio source. Thus, before optical obser-
vations were made, it appeared that all the optical objects were likely
to be physically associated. The brightest of the UV excess objects,
according to Wlérick and Lelièvre, has B = 20.05, B - V = 0.08,
U - B = -0.59. After two seasons of observation, H. E. Smith and I
have found that this object is indeed a QSO, with a redshift z = 1.57
from lines of Mg II, C III], and C IV, whereas the galaxy has a red-
shift less than 10% of this. Accepting the evidence from the radio
structure as indicating that the radio source is one single source with
complex parts, then we have indeed what I would call the best case I
know of a QSO physically associated, it appears, with a galaxy of
much lower redshift. Now there is of course always the possibility
that the QSO is a radio-quiet object which happens by chance to fall
within the radio contours and only appears to be connected with them.
And this points up again the necessity to find out just what is the
surface density of radio-quiet QSOs across the sky.

Nevertheless, the coincidence of the close grouping of 3 UV-excess objects within a few seconds of arc of each other, and one of these being a QSO, is very striking. All three lie less than 20'' from the N system. It is, of course, very desirable that the other two UV-excess objects be observed spectroscopically. Unfortunately, they are 1 1/2 - 2 mag. fainter than the QSO. However, we shall attempt to observe the object that coincides with the compact radio core.

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DISCUSSION

Bahcall: Is there a concentration of the red QSOs towards the galactic plane?

E.M. Burbidge: There is no obvious concentration near the plane, and so I do not believe that we can account for these objects by saying that they are reddened by galactic absorption.

Walsh: Does the proportion of QSOs that are red increase near the Sky
Survey print limit? Identifications down to about 19.5 magnitude based
on accurate radio positions show very few such objects.

E.M. Burbidge: The objects that I have listed are fairly faint and it
may be that there are more of them than has been suspected. Observations
of neutral or red identifications for compact radio sources will, I
hope, lead to a better idea of their frequency and apparent magnitude
distribution.

Kronberg: I have mapped 3C 303 at 3.7 and 11.1 cm (resolution ~ 2.2
and ~ 7" respectively) with the NRAO interferometer, and more recently
at λ6 cm (~ 7" resolution) at Westerbork together with R.G. Strom. An
accurate radio-optical comparison using two deep Palomar 48-inch plates
(taken by S. van den Bergh) enabled us to show that the cores of both
main radio components lie within ~ 1" of two objects which are 16" arc
apart (Kronberg, Ap.J.(Lett) 203, L47, 1976). One of these is a 17th
magnitude N-galaxy (Z = 0.14) and the other a 22nd magnitude member of
a trio of faint objects. Lelièvre and Wlérick (Astron. and Astrophys.
42, 293, 1975) who had independently identified the field have found
that all three faint objects (M_v = 21.70, 19197 and 21.75) have UV
excess. The radio maps at 11 cm and 6 cm show further extended struc-
ture on both sides of the N-galaxy, and confirm the presence of faint
radio structure between the two main radio components. A radio exten-
sion to the southwest of the western radio component includes the
entire trio of UV excess objects. It is the brightest whose redshift
(z = 1.57) has recently been determined.

The fact of the double radio-optical coincidence is curious. Our radio
maps show with virtual certainty that 3C 303 is a single radio system,
and not an accidental super-position of unrelated radio sources. The
question of whether the two systems of different redshift are physically
related or not relies on whether the 20^m quasar and its two fainter
companions coincide only by chance with the western radio component of
3C 303. In any case the optical field is interesting, and the result
underlines the need to do such radio-optical comparisons for more
sources. We need more deep optical plates and spectra, now that we
have detailed multi-frequency radio maps at optical resolution.

Webster: At first glance this looks to be a fairly standard type of
radio source with 2 outer steep-spectrum lobes and one central flat
spectrum component centred on the bright galaxy. Then this seems to me
to be a good case for associating the whole radio source with the
galaxy, but what is there to link the quasar with the preceding radio
lobe?

Kronberg: The quasar with measured redshift lies approximately in the
centre of the southwest extension of the main western radio component,
although not on a compact (< 1") radio core. One of its fainter (also
UV excess) companions *does* coincide within ~ 1" with the bright radio
core of the tadpole-like western component.

P. Véron: Lelièvre and Wlérick (Astron. and Astrophys. 42, 293, 1975) have measured the colors of the faint object which coincides with the western radio component of 3C 303, (a few seconds NE from the QSO whose redshift was measured by M. Burbidge). This very faint object (V = 21.7) has a strong UV excess with U–B = –0.90 ± 0.25, so it is a good quasar candidate. The positional agreement is also very close, since it lies within 1 arc second of the mean Cambridge radio position as determined by Branson *et al.* and by Pooley and Henbest.

Ryle: Concerning the discussion about 3C 303; I looked back at the map published by Pooley & Henbest in 1974. This was made with the 5 km telescope at λ = 6 cm with an angular resolution of 2" arc, and showed an unresolved E component < 1".2 and a W component 4".4 x 1".3, with a strong polarisation in the northerly extension. These early observations also suggested a faint and extensive envelope and showed no feature associated with the large redshift blue object.

In order to examine the low T_s features with better sensitivity we observed the source last night with the 5 km telescope at λ = 11 cm, where the sensitivity for a resolved source is some 10 times better, and the resolution is still 3".7 arc. The map shows a jet running from the compact E source towards the W component, and a faint diffuse extension to the E of the compact source, whose length is comparable with the separation of the main components. The distribution is reminiscent of those of 3C 66 and 3C 219, and suggests that in all these cases the compact source represents the nucleus of a double structure whose components have developed in different ways.

The large redshift blue object does not appear to be associated with any significant radio emission, although the northern blue object lies within the extended W component.
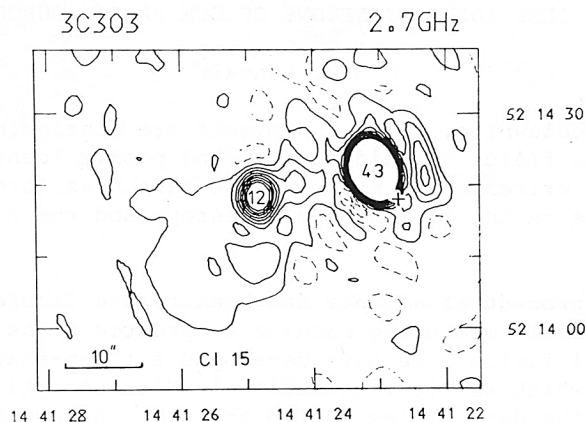
Map of 3C303 made with the 5-km telescope at 2.7 GHz. For the two intense components the higher level contours have been omitted and the peak level is indicated. The cross marks the position of the brightest of the three UV excess objects.

Miller: Is the blue object very near the centre of the western radio component extended, and is it possible to get a spectrogram of it?

E.M. Burbidge: It can be done; it's faint and it's going to take time, but it would be well worth the effort.

Rowan-Robinson: I would like to direct a question to those who identify radio sources with quasars: If there had been only the quasar for which the redshift has been measured and the right hand radio source, would it have been accepted as an identification?

E.M. Burbidge: We would have looked at it as a possible candidate.

Ryle: No, the positional disagreement is far too great and the optical object is not associated with any significant radio emission.

Swarup: For Ooty occultation sources we do not consider any object identified if it is not along the axis of the source or coincident with one component within the error bars.

Hazard: It is doubtful if the QSO near 3C303 would have been identified in the Molonglo Survey. The galaxy would have been considered the more probable identification although the QSO would have been noted and examined spectroscopically. It is my opinion that the claimed associations between QSO's and galaxies etc. is a reflection of a very high background QSO density per sq degree.

Arp: As someone who has actually observed and searched for ultra violet excess objects on photographic plates - I can testify that such a close configuration of strong ultra violet excess objects as the three near 3C303 is extraordinary.

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DEEP IDENTIFICATIONS OF 3CR RADIO SOURCES

M.S. Longair

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Gunn, Kibblewhite, Riley and myself are continuing deep optical surveys of the fields of unidentified and poorly identified 3CR radio sources. Our criterion is $m_{pg} > 19$. We have been fortunate to obtain observing time on the Palomar 5-m telescope and the Kitt Peak 4-m telescope.

A major procedural advance has been to use Kibblewhite's laser scanning automatic measuring machine to produce scans and contour maps of the optical fields. We have developed a three-stage reduction procedure by which we tie together the radio and optical frames of reference on the deep plates to 0.3 arc sec. A further advance is the possibility of obtaining magnitudes at very faint magnitudes by integrating over the digitised image of the optical counterpart. So far we have studied the first 4 fields of our sample and obtained 100% success in our identification programme. These sources are 3C133, 184, 190, 217. 3C190 is a relatively bright galaxy and was previously identified but

the other identifications are believed to be new. In the case of 3C184 (see figure), the estimated magnitude of the galaxy is 23.2 ± 0.5. We have plates of a further 25 fields.

3C 184
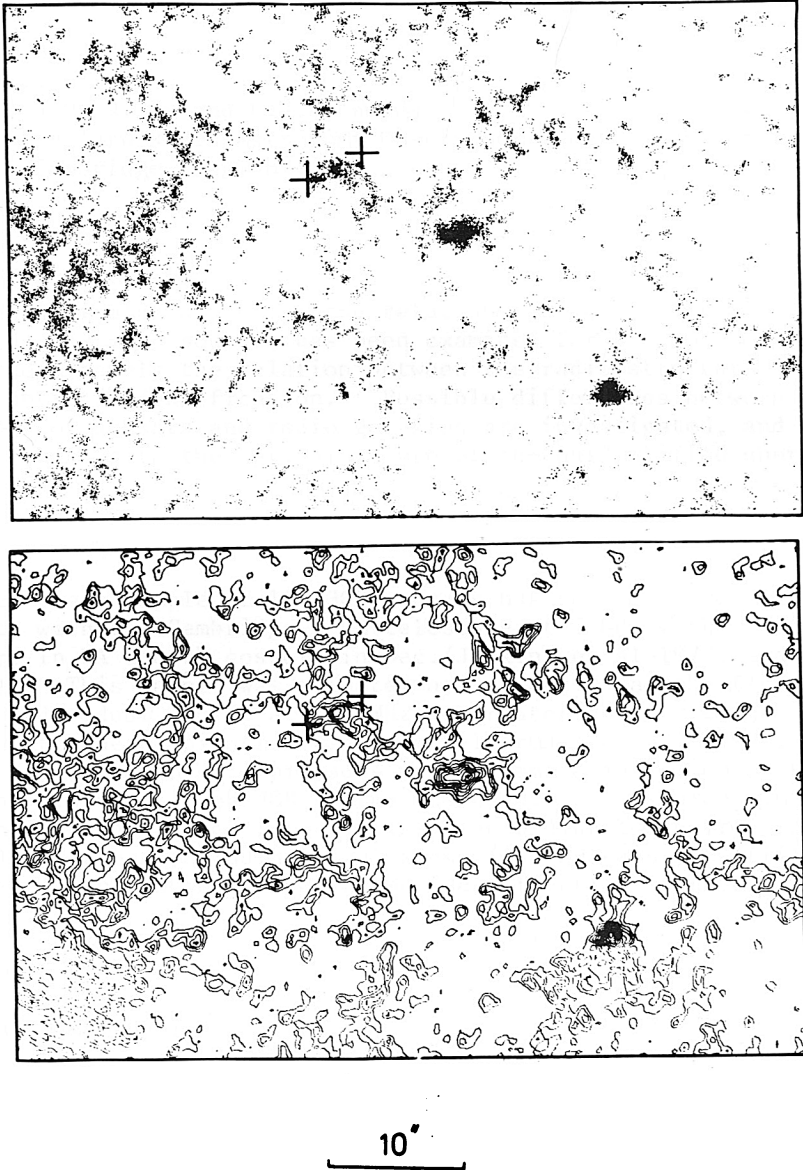
Scans and contour map of the field around 3C 184. The identified galaxy lies between the two crosses.