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ASTRONOMY AND ASTROPHYSICS

Statistical Analysis of Discrepant Redshift Associations

II. QSO-Galaxy and QSO-QSO Pairs

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Summary. The problem of discrepant redshift QSO-galaxies associations is considered here. The correlation found by Burbidge et al. (1972) between angular separation and redshift of the galaxy for close associations is reanalyzed, since we show that *spatial* density fluctuations of nearby galaxies interfere with this relation. However, taking this correction into account greatly decreases (to 10^{-9}) the probability of chance occurrence of these associations. A possible anomaly in the distribution of the high redshifts in QSOs pairs is also pointed out.

Key words: galaxies — quasars — associations — redshift

Introduction

In Paper I (Nottale and Moles, 1978), the statistical significance of discrepant redshift quintets of galaxies was reanalyzed, and it was concluded that present data did not favor the view that they were due to chance projection effects. In the present paper, we are interested in the statistical analysis of quasar–galaxy close associations (Section I). We consider exclusively the associations between 3CR quasars and galaxies of the Catalogue of Galaxies and of Clusters of Galaxies (CGCG, Zwicky et al., 1961–1968) brighter than $m = 14$. We do not discuss here associations with other samples of QSOs and galaxies. It is shown that the clustering of nearby galaxies interferes with the relation between QSO-galaxy angular separation and redshift of the galaxy (Burbidge et al., 1972) in a way not yet considered by various authors having discussed this question, and which increases the significance of the effect. In Section II, the close quasar-quasar associations are studied, and a possible anomaly in their redshift distribution is pointed out.

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I. Galaxy-Quasar Association

1. Introduction

Burbidge et al. (1971, hereafter called B^2S^2) found that four 3C quasars were abnormally close to galaxies from the Reference Catalogue of Bright Galaxies (RC1, de Vaucouleurs and de Vaucouleurs, 1964). The associated probability was only $\sim 5 \times 10^{-3}$. The significance of the effect is confirmed by Kippenham and de Vries (1974) who find in no way such a proximity in their numerical

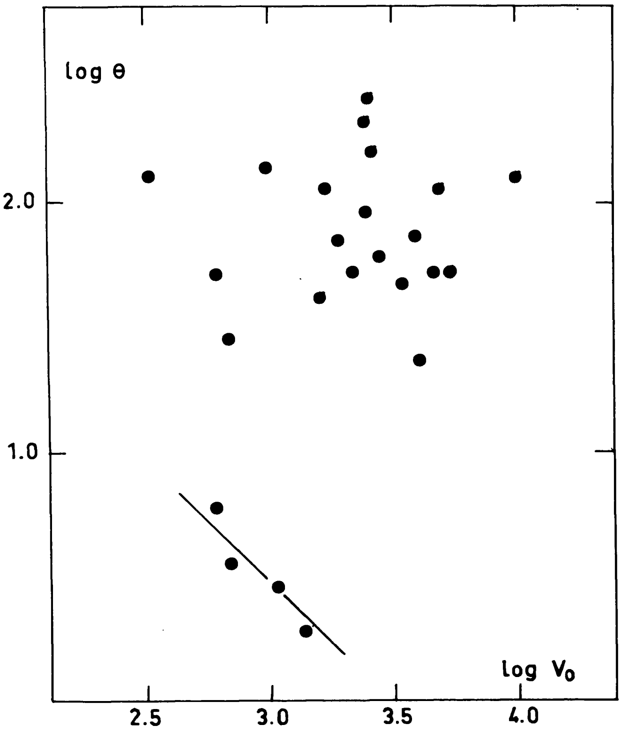

Fig. 1. Logarithmic plot of angular separation θ between a 3C QSO and the nearest CGCG galaxy having $m \leqq 14$ and measured redshift, against radial velocity (corrected for solar motion) of this galaxy, adapted from Nieto (1976). A line of slope -1 is drawn for reference through BOS quasars

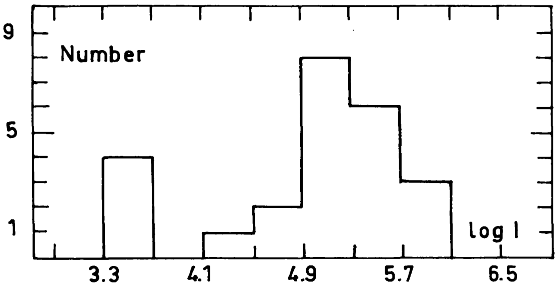

Fig. 2. Distribution histogram of logarithm of linear distances $\log l = \log(\theta V)$ (+ constant). The four B^2S^2 QSOs are clearly separated from the remaining distribution

simulation. Moreover, Burbidge, O'Dell and Strittmatter (BOS, 1972) have found that for these four pairs (and an additional one) there was a linear relation between the angular separation of the quasars and the redshift of the galaxy. No such effect was found by Bahcall et al. (1972) or Hazard and Sanitt (1972) who used other quasar catalogues.

Ozernoi (1974) argues that the BOS relation disappears when every known pair is taken into account. Nieto (1976, 1977) studies the distribution of the nearest CGCG galaxies to quasars. In particular, he shows that though the Burbidge et al. discrepancy is present for CGCG galaxies with $m \leqq 14$, it disappears for CGCG galaxies with $m \leqq 15.7$. His conclusion is that the effect could be the result of statistical fluctuations.

The data presented in Figure 1 are adapted from Nieto (1976). This is a logarithmic plot of QSO-galaxy angular separations θ (between 3C QSOs and CGCG galaxies with $m \leqq 14$) against redshift of the galaxy, V. Radial velocities of galaxies corrected for solar motion are taken from de Vaucouleurs et al. (RC2, 1976).

Figure 2 shows the histogram of $\log(\theta V) = \log l$ values. B^2S^2 four quasars are clearly separated from the rest of the distribution and seem to lie at constant linear distance from the associated galaxies (Burbidge et al., 1972).

2. *Analysis*

The statistical analysis of this effect is made by computing the probability that the nearest galaxy lies at distance r from a quasar (Nieto, 1976; Rose, 1977) that is:

$$P_1(r) = 2\pi\sigma r \exp(-\pi\sigma r^2)$$

where σ represents the surface density of galaxies. One then derives the mean angular distance between a quasar and its nearest galaxy:

$$\bar{\theta} = \int_0^\infty rP_1(r)dr = 1/2\sqrt{\sigma}.$$

Some authors having discussed this effect have taken into account the density fluctuations among galaxies, but they considered only apparent surface densities (i.e. number of galaxies per square degrees). B^2S^2 conclude that clustering does not account for the high number of very close pairs. Effects of apparent clustering on the statistical significance has been also fully studied by Nieto (1976).

We are interested here in the effects of clustering on the inverse correlation between $\log\theta$ and $\log V$ for Burbidge et al. associations. Indeed, let us make the hypothesis that galaxies leading to an apparent surface density σ lie actually at the same distance from us, then constituting groups. Let ρ be their corresponding space density, R their distance, a the radius of the group considered to be a sphere. We suppose $a \ll R$. The galaxies fill a volume $V = 4/3 \cdot \pi a^3$, which is seen under a solid angle Ω. One may write (with $S = 4\pi a^2$)

$$V = aS/3 = a\Omega R^2/3. \tag{1}$$

This volume is related to the number of galaxies:

$$N = \rho V \tag{2}$$

Since we consider small angles ($a \ll R$) the apparent surface density (per square degrees) is related to N and Ω by:

$$\sigma = N/\Omega \tag{3}$$

which gives finally:

$$\sigma = a\rho R^2/3. \tag{4}$$

Considering that the radii a are similar from group to group, and since θ was related to σ through $\bar{\theta} = 1/2\sqrt{\sigma}$, and R to radial velocity assuming Hubble law $V_0 = HR$, we find

$$\log\theta = -\tfrac{1}{2}\log\rho - \log V_0 + \text{constant}. \tag{5}$$

Then a line of slope -1 is predicted by these considerations in the plot $\log\theta$ vs. $\log V_0$. The major part of the dispersion around this line should be due to fluctuations in *spatial* density ρ. If the spatial density of galaxies around the four discrepant QSOs is much greater than around other 3C QSOs, the anomaly found by BOS could be explained from a "classical" point of view. Consequently we try to estimate these densities in the following.

3. *Estimation of Spatial Densities*

The parameter ρ is estimated by counting galaxies with $m \leqq 14$ in CGCG within a given *linear* radius around each 3C QSO. This radius is taken to be $R_0 = 0.5$ Mpc. The distance of the galaxy is estimated from its radial velocity (assuming $H = 100\ \text{km s}^{-1}\ \text{Mpc}^{-1}$). If no galaxy is found within R_0, we use radii $2R_0$, $3R_0$, etc.... Then galaxies around QSOs are searched for redshifts. We confirm by this way our hypothesis that most intervening galaxies lie at the same distance from us. Indeed, we found no more than 10% galaxies having discrepant

Table 1

(1) 3C	(2) NGC	(3) $\log \theta$	(4) $\log V_0$	(5) ρ	(6) $\log l_c$
9	99	1.72	3.73	0.25	1.15
136	2444	1.87	3.60	0.25	1.17
196	2541	1.71	2.78	12	1.04
197	2565	1.67	3.55	1	1.22
205	2685	2.15	2.98	3	1.37
220.2	2859	2.07	3.22	0.75	1.23
232	3067	0.28	3.15	3	−0.33
245	3351	1.44	2.83	36	1.05
249.1	3329	1.83	3.27	1	1.10
254	3600	1.78	3.44	1	1.22
258.4	4138	0.46	3.04	9	−0.02
270.1	4227	1.72	3.68	0.25	1.10
273	4420	1.62	3.19	9	1.29
275.1	4651	0.54	2.87	6	−0.20
280.1	4736	2.10	2.52	28	1.35
286	5127	2.06	3.69	0.062	1.15
288.1	5308	1.71	3.33	2	1.19
309.1	5832	0.79	2.79	4	−0.12
334	6181	2.34	3.40	0.11	1.26
336	6181	2.41	3.40	0.062	1.21
345	MK 501	2.10	4.01	0.012	1.16
351	6307	1.35	3.52	2	1.02
454.3	7448	1.95	3.39	0.56	1.21
455	7479	2.19	3.42	0.22	1.28

redshifts, with respect to the remaining group. We obtain our final values of ρ by correcting for this slight contamination. In Table 1 these values are listed in column (5) with 3C numbers of the QSO (1), NGC number of the nearest galaxy from Nieto (1976) (2), logarithm of angle θ (3) from Nieto (1976) and Arp (1976), logarithm of corrected radial velocity of the galaxy (4) from RC2 and Huchtmeier et al. (1976), and the values of $\log(\theta\rho^{1/2})$ (6).

Another confirmation of the presence of physical groups comes from an expected correlation between $\log \rho$ and $\log V_0$. Indeed, the luminosity function is cut at $m = 14$, and the absolute value of this limit depends on distance. For the more distant groups, one may consider that the steep part of the luminosity function is concerned, with a slope 0.75 in the $\log N - \log m$ diagram (Abell, 1975). This leads to a slope 3.75 in the $\log \rho - \log V_0$ plot. Indeed, the impartial line for $V_0 \geqq 3.0$ has a slope 3.17 ± 0.63, and if one assumes that most errors come from the distance estimation through V_0, one finds 4.04 ± 0.82. The expected value 3.75 is within 1σ of both estimations.

4. Results

The results are very different from expected. First we fully confirm our theoretical relation (5): $\log \theta = -\frac{1}{2}\log \rho - \log V_0 +$ constant. Indeed, in a plot $\log \theta + \log V_0$ against $\frac{1}{2}\log \rho$, a slope -1.020 ± 0.051 is found for associations other than Burbidge's ones. But the main result is that the four discrepant quasars differ even more from the rest of the distribution, as seen in Figure 3, where $\log \theta_c = \log \theta\rho^{1/2}$ (in other terms, the angular separation corrected for spatial density) is plotted against $\log V_o$.

Though the distribution of $\log \theta_c$ values alone has become quite normal, it is not at all the case for the distribution of $\log l_c$ values ($l_c = \theta V \rho^{1/2}$, i.e. linear distance corrected for density effect) as plotted in Figure 4. These two diagrams are to be compared respectively with Figure 1 and 2.

This result means that the spatial density around discrepant quasars is not much greater than for other

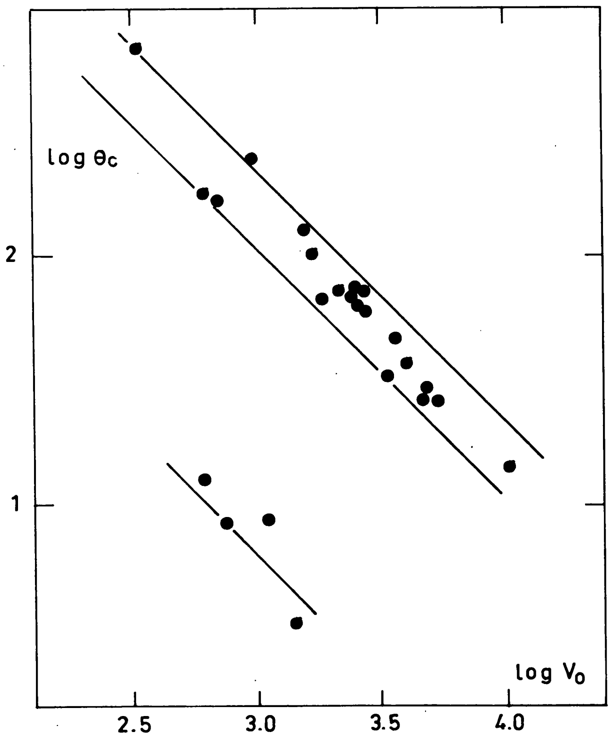

Fig. 3. Same as Figure 1, with angular separations corrected for spatial density effects, i.e. $\log \theta_c = \log \theta\rho^{1/2}$

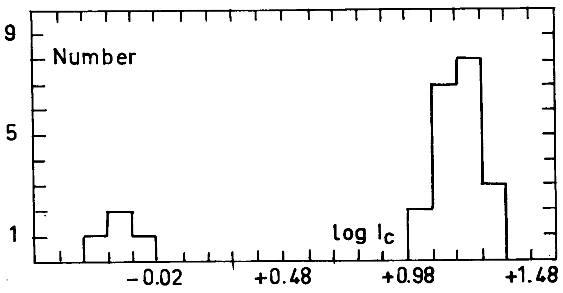

Fig. 4. Same as Figure 2, with linear separations corrected for spatial density effects, i.e. $\log l_c = \log \theta V \rho^{1/2}$. The discrepancy of B^2S^2 QSOs is greatly increased

QSOs, as would have been expected if the effect was to be explained.

One may estimate the level of significance of the discrepancy by the following method: we consider the main (symmetrical) part of the distribution (without the 4 closest associations) of $\log l_c$ values as a test sample with theoretical dispersion σ_1, estimated to be $\hat{\sigma}_1$ using $n_1 = 20$ values. The whole distribution has a dispersion σ_2, estimated to be $\hat{\sigma}_2$, using $n_2 = 24$ values. We know that the ratio $(\hat{\sigma}_2/\sigma_2)^2/(\hat{\sigma}_1/\sigma_1)^2$ follows a Fisher–Snedecor law with $(n_2 - 1, n_1 - 1)$ degrees of freedom. Here the tested hypothesis, we call H_0, is that both distributions are issued from the same population, then $\sigma_1 = \sigma_2$. As a consequence

$$(\hat{\sigma}_2/\hat{\sigma}_1)^2 = F(n_2 - 1, n_1 - 1) = F(23, 19). \tag{6}$$

If we choose now a risk α, under hypothesis H_0 we must have:

$$F_{1-\alpha/2}(23, 19) < (\hat{\sigma}_2/\hat{\sigma}_1)^2 < F_{\alpha/2}(23, 19). \tag{7}$$

(1) Using the values of $\log \theta$ uncorrected for spatial density fluctuation, and $\alpha = 0.002$ one finds $\hat{\sigma}_1 = 0.28$ and $\hat{\sigma}_2 = 0.59$, then $(\hat{\sigma}_2/\hat{\sigma}_1)^2 = 4.44$ which lies outside the interval [0.24, 4.35] defined by (7). The obtained probability $\alpha = 2\ 10^{-3}$ is close to the one derived by B^2S^2, 5×10^{-3}.
(2) Using the corrected values $\log l_c$, one finds $\hat{\sigma}_1 = 0.096$ and $\hat{\sigma}_2 = 0.526$ then $(\hat{\sigma}_2/\hat{\sigma}_1)^2 = 30.02$. The associated probability through the Fisher–Snedecor test is $\alpha \cong 10^{-9}$.

The firm conclusion from these statistical considerations is that the B^2S^2 four QSOs and the remaining sample are issued from two different populations. The significance of the separation is greatly increased when the spatial density of galaxies is considered. Since the B^2S^2 QSOs do not match the distribution of chance associations QSOs, we cannot conclude that the spatial clustering accounts for the inverse correlation found by BOS. On the contrary, our calculation makes stronger the assumption that the four discrepant associations are physical associations.

II. Quasar–Quasar Associations

There are by now five known pairs of QSOs with measured redshifts for both components. (See Table 2 which summarizes present data and references.) Two QSOs are considered to constitute a pair when their angular distance is very faint as compared to what could be expected from chance coincidence of different distance QSOs, that is typically 10^{-2} (see Bahcall and Woltjer, 1974). The striking fact is that *in all cases*, the redshifts of the two components of a pair are discrepant.

The two possible interpretations of these discrepancies are:
(i) both QSOs lie at their cosmological distance, so that the density of QSOs must be far greater than is presently thought, to explain the low probabilities found for example by Bolton et al. (1976);

Table 2

Name	Angular separation (Arc sec)	Magnitude	Redshift	References
0254−334	54	(18.5)	1.915	
Non radio		(16.5)	1.849	
Non radio	66	19.5	2.055	Bolton, J. G., Peterson, B. A., Wills, B. J. Wills, D.: 1976, *Astrophys. J. Letters* **210**, L1
2143−156		17.5	0.700	
Non radio	78	(19.5)	2.041	
2320−035		18.5	1.411	
Ton 155	35	16.6	1.703	Stockton, A. N.; 1972, *Nature Phys. Sci.* **238**, 37
Ton 156		16.0	0.549	
4 C11.50 b	4.8	19	1.901	Wampler, E. J., Baldwin, J. A., Burke, W. L., Robinson, L. B., Hazard, C.: 1973, *Nature* **246**, 203
4 C11.50 a		17	0.4359	

(ii) the association is a physical one, so that at least part of the redshift is non cosmological in origin.

It can be seen in Table 2 that the faintest object in a pair always has a greater redshift. This is not a conclusive fact, since it is compatible with both interpretations (see Jaakkola et al., 1975).

One can also note that there is a poor correlation between angular separation and redshift z_m (correlation coefficient $\rho = 0.69$, slope 1.27 ± 0.77), similarly to the QSO-galaxy close association case. (We call z_m and z_M the smaller and greater redshifts in a pair.) A more striking fact is the small dispersion of z_M values ($\langle z_M \rangle = 1.923$, $\hat{\sigma}_M = 0.142$). This can be connected with a highly significant period found by Karlsson (1977) in the distribution of log $(1 + z)$ values for 574 QSOs in the Burbidge et al. (1977) list, since it is noticeable that the five z_M values fall in one of the peaks, at $z \sim 1.9$.

We try to estimate the statistical significance of this coincidence in the following way. First, the analysis is restricted to sources with $z \leqq 3$ for completeness, following Karlsson. Second, we define the peak at $z \sim 1.9$ from Figure 1 in Karlsson (1977) as objects with $1.7 \leqq z < 2.1$. The peak contains 97 quasars. Third, we consider that for each pair having a given z_m, the probability that z_m be in the peak is given by:

$$P(z_m) = N(z_0, 2.1)/N(z_m, 3)$$

where $z_0 = 1.7$ if $z_m \leqq 1.7$ and $z_0 = z_m$ if $1.7 \leqq z_m < 2.1$.

$N(z_1, z_2)$ is the number of sources whose redshifts lie in the interval $[z_1, z_2]$. Then the probability that the five z_M values would lie in the peak is

$$P = \prod_{i=1}^{5} P(z_{m_i}).$$

We find a small probability, $P = 3.4 \times 10^{-3}$. This result must be considered with caution, since this is an a posteriori probability and since there is a small number of QSO pairs. Then it could easily be the result of statistical fluctuations. (For example the probability that four z_M fall in the peak is 0.04, which is an acceptable value.)

This coincidence of the high redshift in a QSO pair with a peak in the redshift distribution should be confirmed with new pairs before a conclusion can be reached.

However, it supports Karlsson's result that QSOs for which there is evidence that their distances are much smaller than those inferred from their redshifts (BOS quasars and quasars which showed "superluminal" expansions), have redshifts close to the peaks. This could be a key for further understanding of periodicities in the redshift distribution of QSOs.

III. Conclusions

In this paper, we examined two effects which are considered as major arguments for the existence of non cosmological redshifts, that is the Burbidge et al. line for QSO-galaxies associations and the quasar-quasar pairs. It is recalled that redshifts are always discrepant in these pairs, and a possible anomaly in the distribution of the higher redshifts in a pair is discussed in connection with periodicity found by Karlsson (1977) in $\log(1 + z)$ values for QSOs.

But our main result concerns QSO-galaxy associations: we have shown that when QSO-galaxies angular separation are plotted against distance of the galaxy, the classical statistical analysis in term of apparent surface density (galaxies per square degrees) was no more adapted due to spatial clustering of galaxies. Taking this bias into account greatly increases the significance of the separation between the chance associations and the four discrepant quasars. This result, though it cannot be considered conclusive due to its statistical nature, reinforces in the authors' opinion the necessity to consider seriously the hypothesis that a large part of the redshifts of some quasars could be non cosmological in origin.

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References

Abell, G.O.: 1975, Stars and Stellar Systems, vol. IX, ed. Sandage, Chicago

Arp, H.C.: 1976, I.A.U. Colloquium 37, C.N.R.S. Colloquium 263, ed. Balkowski and Westerlund, Paris

Bahcall, J.N., McKee, C., Bahcall, N.: 1972, *Astrophys. Letters* **10**, 147

Bahcall, J.N., Woltjer, L.: 1974, *Nature* **247**, 22

Burbidge, E.M., Burbidge, G., Solomon, P., Strittmatter, P.: 1971, *Astrophys. J.* **170**, 233

Burbidge, G., O'Dell, S., Strittmatter, P.: 1972, *Astrophys. J.* **175**, 601

Burbidge, G., Crowne, A.H., Smith, H.E.: 1977, *Astrophys. J. Suppl.* **33**, 1

Hazard, C., Sanitt, N.: 1972, *Astrophys. Letters* **11**, 77

Huchtmeier, W.K., Tammann, G.A., Wendker, H.J.: 1976, *Astron. Astrophys.* **46**, 381

Jaakkola, T., Donner, K.J., Teerikorpi, P.: 1975, *Astrophys. Space Sci.* **37**, 301

Karlsson, K.G.: 1977, *Astron. Astrophys.* **58**, 237

Kippenham, R., de Vries, H.: 1974, *Astrophys. Space Sci.* **26**, 131

Nieto, J.L.: 1976, Thèse 3e cycle, Université Paris

Nieto, J.L.: 1977, *Astron. Astrophys. Suppl.* **28**, 363

Nottale, L., Moles, M.: 1978, *Astron. Astrophys.* **66**, 355 (Paper I)

Ozernoi, L.: 1974, I.A.U. *Symposium* **63**, p. 73

Rose, J.A.: 1977, *Astrophys. J.* **211**, 311

Vaucouleurs, G. de, Vaucouleurs, A. de: 1964, Reference Catalogue of Bright Galaxies, University of Texas (RC1)

Vaucouleurs, G. de, Vaucouleurs, A. de, Corwin, H.G.: 1976, Second Reference Catalogue, University of Texas (RC2)

Zwicky, F., Herzog, E., Wild, P., Karpowicz, M., Kowal, T.C.: 1961–1968, Catalogue of Galaxies and Clusters of Galaxies, in 6 volumes, Pasadena, California Institute of Technology (CGCG)