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Oort, J.H.

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Superclusters at large redshifts. Can protosuperclusters and the birth of "pancakes" be observed?

J.H. Oort

Sterrewacht-Huygens Laboratorium, Postbus 9513, 2300 RA Leiden, The Netherlands

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Summary. The article starts from the working hypothesis that throughout the universe the luminous matter is largely concentrated in supercluster structures. It then follows that the Lyman α absorption lines in quasars are connected with this structure, and that they can give information on superclustering at large redshifts.

Some direct evidence for the existence of (super)clustering at large redshifts is discussed. The supposition of a relation between superclusters and Ly α lines is supported by the observation that the mean separation along a line of sight is similar for the two phenomena. The fine-structure observed in nearby superclusters might explain the absence of a correlation between the velocities of the Ly α lines in the two neighbouring quasars observed by Sargent et al.

The gas which produces the lines has a high degree of ionization (about $10^4:1$). If, as has been suggested, this is due to the uv radiation of quasars, the ionization might drop abruptly at $z \sim 3.5$, prior to the enormous rise in the density of very luminous quasars. The burst of pancake formations which may have given rise to the high quasar density would presumably have occurred around $z=4.5$. The hydrogen in these pancakes, and in the protopancakes at larger z, may have been largely neutral up to the appearance of the quasars, and may in that case have produced observable radiation in the 21-cm line at frequencies between 280 and 150 MHz. Estimates are given of the expected brightness temperatures, angular sizes and separations in velocity.

Key words: superclusters – "pancakes" – Ly α forest – intergalactic gas

1. The supercluster structure of the universe

Considerable evidence has been accumulated that galaxies are generally concentrated in large structures separated by similarly large voids. The structures, or "superclusters", have dimensions ranging from several tens to several hundreds Mpc[1], the smaller ones being the most common[2]. Many superclusters have strongly elongated shapes; the average axial ratio may be about 4:1.

Judging from the nearest superclusters we infer that they have intricate internal structures (cf. Tully's, 1982, maps of the Local Supercluster, and various investigations of the Perseus supercluster: Einasto et al. 1980; Giovanelli et al., 1983). The substructures in the Local Supercluster have apparent widths of 3–4 Mpc; the actual widths may be still smaller; many of them lie in a plane layer (a "pancake") of half-density thickness of only 1.5 Mpc. Sometimes there is striking filamentary structure. The 67 Mpc long principal branch of the Perseus superluster has a thickness of $2\overset{\circ}{.}5$ or ~ 4 Mpc, while the narrowest filament in this branch is only $1\overset{\circ}{.}7$, or 3 Mpc, wide. That filamentary structures may be common is indicated by the existence of another long filament, in Lynx-Ursa Major, at the same distance as the Perseus supercluster. For this filament Giovanelli and Haynes (1982) give a width of $\sim 1\overset{\circ}{.}7$. Narrow filamentary structure on a smaller scale has also been observed in the Coma supercluster (Fontanelli, 1982). An indication that superclusters may mainly consist of filamentary features is provided by two other phenomena: (a) the fact that the major axes of Abell clusters tend to be directed towards the nearest neighbouring cluster (Binggeli, 1982), and (b) the lack of correllation in the Ly α absorption lines observed in two neighbouring quasars (see below).

Statistical information on superclustering is furnished by the Harvard-Smithsonian Center for Astrophysics (CfA) redshift survey (Davis et al., 1982). The average length of a supercluster is estimated to be about 30 Mpc. Their average separation on a line of sight is about 240 Mpc. The number density may be roughly estimated at 9 per 10^6 Mpc^3.

When we consider a larger region we see that there exists also a class of much more powerful superclusters. This is most evident when studying superclusters of rich clusters. In a recent investigation extending to 500 Mpc distance Bahcall and Soneira (1984) find 0.09 such structures per 10^6 Mpc^3, a hundred times less than the density for the common superclusters quoted above. Their superclusters contain on the average 3.2 rich Abell clusters, as against 0.10 in the superclusters of the CfA survey.

The question to which the present article is mainly addressed is: since when has superclustering existed?

Our direct knowledge of clustering at large redshifts is poor. The most definite case is that of three quasars at $z=2.05$ near M 82. They have redshifts of 2.048, 2.054, and 2.040, respectively, and lie within a circle of $1\overset{'}{.}1$, or 0.1 Mpc, radius (Burbidge et al., 1980). The probability of a chance coincidence is so small that we are justified in believing this to be a real cluster. In a general search for related quasars Oort et al. (1981) found two pairs at very large redshifts. One pair, with $z=3.14$ and 3.16, respectively, and a separation of $0\overset{\circ}{.}54$, or 13.9 Mpc, is almost certainly real; the reality of the other

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[1] Throughout this article the distance scale is based on a Hubble constant of 50 km s^{-1} Mpc^{-1}

[2] A general account of such structural features may be found in Oort, 1983

pair, which has redshifts of 2.85 and 2.83, and a separation of 1°18 (31.5 Mpc), is less certain, but the chance of its being spurious is rather small.

Since this article was written some new evidence for the existence of clustering at large and moderately large redshifts was given in a communication by Shaver (1984). In a search which appears free from bias he found, after excluding two probable cases of gravitational lensing, 10 quasar pairs with transverse separations $<5\,h^{-1}$ Mpc and redshift differences $<2500\,\mathrm{km\,s^{-1}}$, while only 2.4 such pairs would be expected in a random distribution. These numbers were computed for an open universe ($q_0=0$) and comoving cluster sizes ($h=$ the Hubble constant expressed in units of $100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$). Three of the pairs are derived from the triplet of quasars near M82 described above. Shaver tentatively concludes that the degree of clustering at $z\sim 2$ was not radically different from that at present.

Though the above evidence is fragmentary it is important in indicating that clustering, and probably superclustering, seems to occur up to redshifts around 3.

Because there are apparently no temperature fluctuations in the 3K background radiation of sufficient amplitude to produce by themselves collapses at such early times the above observations indicate also that the universe must consist mostly of weakly interacting particles.

The considerations described in the present article are based on the working hypothesis that superclustering like that observed in our surroundings has existed since at least $z=3$.

2. The Lyman α absorption lines in quasars

All distant quasars show a "forest" of Ly α absorption lines shortward of their emission redshifts (Sargent et al., 1980, 1982; Sargent and Boksenberg, 1983; Chen et al., 1981; Peterson et al., 1984). Three different suggestions have been made for the origin of these absorptions: (a) large halos surrounding galaxies, (b) gas distributed throughout superclusters, (c) a special sort of intergalactic clouds.

First consider (a). The average number of Ly α absorption lines per unit interval of z, reduced to the present epoch, for a universe of critical density, is 33 according to Sargent et al. (1980). For $H_0=50\,\mathrm{km^{-1}\,Mpc^{-1}}$ this corresponds to a mean free path between absorbers of 183 Mpc. Galaxies with luminosity of the order of L_* in Schechter's luminosity function would have to have radii of 590 kpc to give that many Ly α absoprtions. Though this is far larger than any halos ever observed in emission the interpretation cannot be entirely ruled out. Two cases have indeed been found where a quasar shows an absorption system at a redshift coinciding with the emission redshift of a foreground quasar at a lateral distance of about 500 kpc from the image of the first quasar, indicating that quasars can have halos of at least this radius. The cases concerned are the quasar pair Q 0307–195 A and B, at $z=2.144$ and 2.122 (Shaver and Robertson, 1983), and the pair Q 0028 + 003/Q 0029 + 003 at $z=2.222$ and $z=1.732$, respectively (Shaver et al., 1982). The H I column densities required for the Ly α absorptions are exceedingly small. Sargent et al. estimate them to be around $10^{14}\,\mathrm{cm^{-2}}$, which is at least four orders of magnitude lower than the lowest column density observable in 21-cm H I emission. It should be noted that these halos need not be smooth: they might consist of loose clouds or streams.

An alternative possibility is that the Ly α absorptions would not be due to large galaxies of the L_* kind, but might instead have occurred in the surroundings of dwarf galaxies. Down to luminosities of $0.01\,L_*$ these are about 1500 times more numerous, so that their "halo" radii need only be ~ 15 kpc to yield the required density of Ly α lines. The possibility that dwarf galaxies might be the absorbers of the Ly α lines has also been suggested by Fransson and Epstein (1982). They investigated the possibility that stellar winds caused by bursts of star formation would produce shells of the appropriate size.

Sargent et al. rejected (a) for two reasons. In the first place they remarked that halos of the required sizes would partly overlap. This may indeed be so; but it does not preclude the possibility of their existence. In the second place they remarked that the Ly α lines fail to show the clumpiness and clustering which is so pronounced in the distribution of galaxies. For these reasons they suggested that the lines would be due to an unknown species of intergalactic clouds [possibility (c)].

I doubt whether the hypothesis of galactic halos can be discarded on the ground that the lines show no evidence of clustering; for such halos could not remain independent in places where the galaxy density is much above average. The lack of clustering in the lines would in this case be a natural consequence of the required large sizes. For these reasons there would seem to be no motive for introducing an entirely new sort of objects to explain the Ly α lines.

Let us finally consider possibility (b). It has been suggested (Oort, 1981) that the Ly α lines might come from primeval "pancake" gas left over from formation of galaxies. The suggestion was prompted by the observation that the average separation between the lines was remarkably close to the estimated mean distance between superclusters. According to present estimates this is ~ 240 Mpc (cf. Oort, 1983, p. 393), which is not very different from the separation of 183 Mpc quoted above for the Ly α lines. Both values are quite uncertain. But their approximate correspondence is plausible if everything in the universe is concentrated in superclusters, independent of the question whether the lines are due to distributed gas, galactic "halos", or the clouds suggested by Sargent et al. An important property of the Ly α absorption systems is the considerable underabundance of heavy elements (Sargent and Boksenberg, 1983).

An extremely interesting observation was made by Sargent et al. (1982). They measured with high resolution the Ly α lines in two quasars (at $z=2.518$ and 2.605, respectively) which are separated by only 3′1, corresponding to 1.4 Mpc in the universe considered in the present article. A pronounced correlation between the Ly α lines in the two quasars was expected in the case that the lines are absorbed by objects situated in superclusters. But no evidence of correlation was found. If our working hypothesis of a general supercluster structure in the universe is true the absence of pronounced correlation leads to the conclusion that the lines of sight to the two quasars have passed largely through different superclusters. The dimensions of the order of 30 Mpc attributed to the common superclusters would at first sight seem to exclude this. But, as indicated in Sect. 1, superclusters may often have filamentary structures, with widths of no more than 3 or 4 Mpc, while the near-by, well-studied superclusters show intricate substructures with similar widths. At $\langle z\rangle \sim 2$ the general dimensions of superclusters must have been smaller. Quite possibly their internal filamentary structures have likewise been thinner in the past.

For these reasons the lack of correlation between the lines in the two neighbouring quasars may not exclude the idea that the lines formed in objects or gas situated in filamentary structures in superclusters.

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Recently Foltz et al. (1984) have observed Ly α lines in the two components of the gravitational-lens quasar 2345 + 007 A, B. They found several Ly α absorption lines in common between the two images, which have a separation of 7″.3. These observations yield a lower limit of order 5–25 kpc for the size of the Ly α clouds. One or two lines may *not* be present in both images. If these differences are real (which is still rather uncertain) they would point to an equally small *upper* limit for the cloud sizes. Such dimensions are similar to those estimated above for the hypothetical dwarf galaxy halos.

Whatever the Ly α absorbers are supposed to be it appears plausible to assume that their distribution in space follows the general trend of most of the matter in the universe to be concentrated in superclusters, and that therefore, in accord with the working hypotheses formulated in Sect. 1, the Lyman α forest reflects the superclustering in the universe at earlier periods.

The most distant quasars in which the forest has been observed are Q 1442 + 101 at $z = 3.56$ (Peterson et al., 1984) and Q 2000–330 at $z = 3.78$ (Sargent and Filippenko, 1983). Up to those redshifts the forest appears to continue with unabated density; there is nothing to indicate that we are approaching its beginning.

Yet, a radical change is likely to have occurred at an only slightly larger redshift.

3. The evolution of quasars and the ionization of the intergalactic gas

The density of quasars increases strongly with z. According to a recent estimate by Schmidt and Green (1983) the density of the most luminous quasars (M between –28 and –29) at $z = 2.5$ is $\sim 10^7$ times their local density. It increases still further up to $z \sim 3$, after which the distribution begins to flatten. A special search at higher redshifts by Osmer (1982, 1983) who surveyed 5 square degrees to a magnitude of ~ 20.0 with an equipment that would show quasars between $z = 3.7$ and 4.7 if they existed, failed to show any, whereas an extrapolation of the densities observed at $z < 3.5$ yielded an expected number of ~ 12 for an Einstein – de Sitter universe, and ~ 22 for a universe with $\Omega = 0.2$. There is thus a clear indication of a break in the steep density increase around $z = 3.5$. The data are still too scarce to define the *exact* redshift at which this sets in, or to determine whether it is preceded by an era of *much* lower quasar density.

The steepness of the density increase around $z = 3$ does suggest a strong burst of quasar formation around that epoch. In the "pancake" theory (Zeldovich, 1970; Shandarin et al., 1983 and references therein) this means that prior to this there must have been a brief period of intense formation of "pancakes" or "filamentary" structures. Before this period the number of quasars may have been low.

Sargent et al. (1980) have suggested that the ionization of the intergalactic medium at $z < 4.0$, where the Ly α lines are observed, was due to quasar radiation. They estimated a degree of ionization of the order of 10^4. Recent measurements of the ratio of Ly β to Ly α in the Ly α absorption spectra by Norris et al. (1983) have confirmed Sargent et al.'s estimates. The ionization may, however, also have been due to matter falling into the pancakes. If the ionization is due to quasar radiation the medium would have been neutral before the advent of quasars. It is then interesting to inquire what the supercluster structures responsible for the Ly α absorptions would have looked like in that era, and whether they might be observable.

4. Expected properties of protosuperclusters

If, as suggested in the foregoing, the enormous rise in the density of powerful quasars around $z = 3$ to 3.5 is ascribed to a concentration of pancake collapses these should have taken place around $z = 4.5$, if we assume that the formation of a galaxy from the pancake medium takes of the order of a hundred million years, and that it would take about half or one billion year to develop an active nucleus like a quasar. The first supercluster galaxies may then have formed around $z = 4$. Before this era the superclusters would have been gaseous, and presumably neutral up to the appearance of quasars.

If we adopt a number density of 9 superclusters per comoving volume of 10^6 Mpc^3 as estimated above from the CfA survey, and if we suppose that the mass in the Einstein – de Sitter universe is equally divided between voids and superclusters then the average mass of a supercluster sould be $4\ 10^{15}\ M_\odot$. The baryon density must be about 1/10th of the critical density in order to have produced the correct helium and deuterium abundance. If the helium abundance is 35% by weight the hydrogen mass of an average supercluster would thus be $2.6\ 10^{14}\ M_\odot$. If the supercluster has expanded like the universe it would at $z = 4.5$ have had an average diameter of about 5 Mpc, and a column density of $1.7\ 10^{21}$ H cm^{-2}.

If the universe consists principally of heavy neutrinos, or other weakly interacting particles, these would be the first to collapse into a pancake. Baryons would at first collect in a thin central layer of the "neutrino" pancake. In this layer the gas ionized during the collapse would cool rapidly. (cf. the general survey by Shandarin et al., 1983 and references therein). This thin H I layer may be observable. Suppose it contained a fraction f of the total baryon mass of the supercluster finally formed through the continuing infall. The H I column density in the initial pancake would then be $1.7 f\ 10^{21}$ H cm^{-2}. In the following we shall tentatively assume f to be 0.2.

To obtain an estimate of the H I brightness temperature we need to know the spread in velocity. This is likely to be due mainly to differential expansion of the pancake over the observed beamwidth. Suppose this to be b arcmin, corresponding at $z = 4.5$ to 0.36 b Mpc, and suppose, further, that the pancake expands in its plane with the Hubble expansion, which in the universe considered in this article is 645 km s^{-1} Mpc^{-1} at $z = 4.5$. At an average angle of 30° between the pancake and the line of sight the velocity range over a beam of b' would then be 400 b km s^{-1}. The column density for such a pancake being twice the face-on column density estimated above the number of hydrogen atoms per cm^2 per (cm s^{-1}) would then be $8\ 10^{13}\ f/b$. For a comoving observer the corresponding brightness temperature would be 4.6 f/b; for an observer on the Earth this has to be multiplied by a factor $(1+z)^{-1}$, and thus becomes 0.8 f/b. With a beamwidth of 1′, such as can be reached by a large synthesis telescope, and taking $f = 0.2$ (a value suggested by Sunyaev and Zeldovich, 1972) the expected temperature would be of the order of 0.2 K.

This has to be measured against the background of non-thermal radiation from the Galaxy. From surveys at frequencies of 150 MHz (Landecker and Wielebinski, 1970) and 408 MHz (Haslam et al., 1970 and 1974) I infer that in regions of minimal brightness the brightness temperatures are about 175 K and 20 K, respectively. Interpolation to the frequency of the hydrogen line at $z = 4$ (284 MHz) and $z = 6$ (203 MHz) gives temperatures of 43 K and 90 K. According to the observations by Haslam et al. the background in the extended areas of lowest radiation shows fluctuations of the order of 10% on scales of the order of 1°. Similar unevenness is indicated in the survey of Berkhuysen (1972) at 820 MHz. Although the background would be a serious problem it may be possible with sufficiently sensitive receivers to observe objects having a small width in frequency.

Evidently there are many uncertain factors in the estimated H I brightness temperatures of the protosuperclusters: the velocity spread may be different; the estimate of 0.2 for the fraction f may be wrong; the fraction of the total mass lying in the voids may be less than the 50% assumed; the density of the universe may differ from the critical value. And, finally, there is no certainty about the correctness of the adiabatic scenario for the formation of gaseous pancakes.

The angular dimension corresponding to an estimated linear size of an average supercluster of ~ 5 Mpc at $z=4.5$ is $0\overset{\circ}{.}23$. With a density of 9 superclusters per $10^6\,\mathrm{Mpc}^3$ as estimated in Sect. 1 the average projected distance between adjacent superclusters is 17 Mpc, corresponding to 3 Mpc, or $0\overset{\circ}{.}14$, at $z=4.5$.

A rough estimate may be made of the spacing to be expected between the lines. Sargent et al. (1980) find an average of 61 lines per unit interval of z for their quasars with $\langle z_{\mathrm{em}}\rangle = 2.44$. There is some evidence of evolution: Young et al. (1982) find that the number of lines per unit interval of z, $N(z)$, varies as $(1+z)^{\gamma}$, with $\gamma = 1.81 \pm 0.48$. Assuming this evolution the average spacing in z would be 0.007 at $z=4.5$, corresponding to $400\,\mathrm{km\,s^{-1}}$. With velocity widths of $400\,b\,\mathrm{km\,s^{-1}}$ as estimated above the emission lines within a beam of $1'$ might not be separable.

A very similar computation has previously been made by Sunyaev and Zeldovich (1974; 1972). They considered proto*clusters* of galaxies instead of *superclusters*. They derived brightness temperatures of the order of 1 K for the smaller regions occupied by the clusters. Following Sunyaev and Zeldovich's predictions a search for H I in protoclusters at $z=3.33$ and 4.92 (corresponding to 328 MHz and 240 MHz for the hydrogen line) was carried out by Davies et al. (1978), using a 2.5 MHz bandwidth, corresponding with $\sim 3000\,\mathrm{km\,s^{-1}}$, and beamwidths of $50'$ and $68'$, respectively. No measurable signal was found, but the authors came fairly close to the predicted intensities.

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References

Bahcall, N.A., Soneira, R.M.: 1984, *Astrophys. J.* **277**, 27

Berkhuysen, E.: 1972, *Astron. Astrophys. Suppl.* **5**, 263

Binggeli, B.: 1982, *Astron. Astrophys.* **107**, 338

Burbidge, E.M., Junkkarinen, V.T., Koski, A.T., Smith, H.E., Hoag, A.A.: 1980, *Astrophys. J. Letters* **242**, L55

Chen, J., Morton, D.C., Peterson, B.A., Wright, A.E., Jauncey, D.L.: 1981, *Monthly Notices Roy. Astron. Soc.* **196**, 715

Davies, R.D., Pedlar, A., Mirabel, I.F.: 1978, *Monthly Notices Roy. Astron. Soc.* **182**, 727

Davis, M., Huchra, J., Latham, D.W., Tonry, J.: 1982, *Astrophys. J.* **253**, 423

Einasto, J., Jôeveer, M., Saar, E.: 1980, *Monthly Notices Roy. Astron. Soc.* **193**, 353

Foltz, C.B., Weymann, R.J., Röser, H.J., Chaffee, Jr. F.H.: 1984, *Astrophys. J. Letters* **281**, L1

Fontanelli, P.: 1982, in *The Comparative* H I *Content of Normal Galaxies*, eds. M. Haynes, R. Giovanelli, Natl. Radio Astron. Obs., Green Bank, W. Va., pp. 112–115

Fransson C., Epstein, R.: 1982, *Monthly Notices Roy. Astron. Soc.* **198**, 1127

Giovanelli, R., Haynes, M.P.: 1982, *Astron. J.* **87**, 1355

Giovanelli, R., Haynes, M.P., Chincarini, G.L.: 1983, preprint

Haslam, C.G.T., Quigley, M.J.S., Salter, C.J.: 1970, *Monthly Notices Roy. Astron. Soc.* **147**, 405

Haslam, C.G.T., Wilson, W.E., Graham, D.A., Hunt, G.C.: 1974, *Astron. Astrophys. Suppl.* **13**, 359

Landecker, T.L., Wielebinski, R.: 1970, *Austral. J. Phys. Astrophys. Suppl.* **16**, 1

Norris, J., Hartwick, F.D.A., Peterson, B.A.: 1983, *Astrophys. J.* **273**, 450

Oort, J.H.: 1981, *Astron. Astrophys.* **94**, 359

Oort, J.H., Arp, H., de Ruiter, H.: 1981, *Astron. Astrophys.* **95**, 7

Oort, J.H.: 1983, *Ann. Rev. Astron. Astrophys.* **21**, 373

Osmer, P.S.: 1982, Astrophys. J. **253**, 28

Osmer, P.S.: 1983, in *Quasars and Gravitational Lenses*, ed. J. P. Swings, 24th Liège Intern. Astrophys. Colloquium, p. 51

Peterson, B.A., Morton, D.C., Chen, J.S., Wright, A.E., Jauncey, D.L.: 1984, *Astrophys. J.* (submitted)

Sargent, W.L.W., Young, P.J., Boksenberg, A., Tytler, D.: 1980, *Astrophys. J. Suppl.* **42**, 41

Sargent, W.L.W., Young, P., Schneider, D.P.: 1982, *Astrophys. J.* **256**, 374

Sargent, W.L.W., Boksenberg, A.: 1983, in *Quasars and Gravitational Lenses*, ed. J. P. Swings, 24th Liège Intern. Astrophys. Colloquium, p. 518

Sargent, W.L.W., Filippenko, A.: 1983, *Astrophys. J.* (in preparation)

Sschmidt, M., Green, R.F.: 1983, *Astrophys. J.* **269**, 352

Shandarin, S.F., Doroshkevich, A.G., Zeldovich, Ya.B.: 1983, *Usp. Fiz. Nauk* **139**, 83; *Sov. Phys. Usp.* **26**, 46

Shaver, P.A.: 1984, *Astron. Astrophys. Letters* **136**, Lg. Also *Inner Space/Outer Space*, Proc. Fermi Lab. Conf., 2–5 May 1984, (to appear)

Shaver, P.A., Boksenberg, A., Robertson, J.G.: 1982, *Astrophys. J. Letters* **261**, L7

Shaver, P.A., Robertson, J.G.: 1983, *Astrophys. J. Letters* **268**, L57

Sunyaev, R.A., Zeldovich, Ya.B.: 1975, *Monthly Notices Roy. Astron. Soc.* **171**, 375

Sunyaev, R.A., Zeldovich, Ya.B.: 1972, *Astron. Astrophys.* **20**, 189

Tully, R.B.: 1982, *Astrophys. J.* **257**, 389

Young, P., Sargent, W.L.W., Boksenberg, A.: 1982, *Astrophys. J.* **252**, 10

Zeldovich, Ya.B.: 1970, *Astron. Astrophys.* **5**, 84