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MICROVARIABILITY OF OJ 287 DURING A FLARE[1]

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RESUMEN

Presentamos observaciones de microvariabilidad en la emisión óptica de OJ 287, detectadas durante una ráfaga ocurrida en enero de 1994. Al seguir el comportamiento de OJ 287 a lo largo de la duración completa de este evento, observamos un comportamiento típico de ráfaga tipo sincrotrónico, con un aumento de brilllo pronunciado al inicio, y posteriormente una disminución de brillo lenta. La ráfaga presentó una estructura de doble pico, probablemente debida a la superposición de dos eventos similares ocurridos con un día de separación. Las microvariaciones se observaron superpuestas a la curva de luz global, durante al menos seis noches (de diez). Identificamos dos tipos distintos de microvariaciones: ráfagas superpuestas de menor amplitud y variaciones de brillo suaves de tipo sinusoidal. Los tiempos característicos de estas microvariaciones van de minutos a horas, y nada sugiere un comportamiento de tipo periódico. Se da una discusión de los posibles mecanismos físicos responsables de las variaciones de brillo a distintas escalas de tiempo y distintas amplitudes.

ABSTRACT

We present microvariability observations of OJ 287, taken during a small flare in January 1994. We can follow the behaviour of OJ 287 during the whole flare. The event has a synchrotron flare shape, with a steep ingress and slower egress, and a double peak structure most likely due to two similar flares occurring a day apart. Microvariability is observed on top of this flare during at least six nights, out of ten. Two types of microvariability events can be identified: small flares and smooth sinusoidal variations. The time scales are of the order of minutes to hours. We do not find any periodic or quasi-periodic variations. A brief discussion on the possible mechanisms responsible for the different scales and types of variability is given.

Key words: **GALAXIES - ACTIVE — GALAXIES - BL LACERTAE OBJECTS - INDIVIDUAL (OJ 287) — GALAXIES - PHOTOMETRY**

1. INTRODUCTION

Observed microvariability in quasars and BL Lac objects can probe the smallest spatial dimensions in these extragalactic objects. Using light travel arguments, the sizes of the emitting regions are found to be about the size of the Solar System (e.g., Carini et al. 1992). Microvariability has been observed to occur randomly in almost every BL Lac object where it has been searched for (e.g., OJ 287, BL Lac, Carini et al. 1992, and references therein). Most of these searches for microvariabilty have been, unfortunately, short snapshot type observations, when one has monitored an object for a few hours during a couple of nights. Carini et al. (1992) detected changes as large as 0.08 mag/hr in OJ 287 and 0.1 mag/hr in BL Lac during their campaign that lasted a few years. They observed OJ 287 and BL Lac a couple of times per year during several years. So far no

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systematic long term monitoring campaigns for microvariability studies have been conducted; long term meaning several days, with 24 hour coverage. Although the existence of microvariability is now fully accepted (e.g., Wagner & Witzel 1995), its reality was doubted or ignored for a long time. The first report on microvariability (or "flickering") for AGN, dates back to Mathews & Sandage (1963)! Their finding was ignored, very probably due to the highly transient behaviour of microvariability, which makes it extremely difficult to confirm. The random nature of microvariability makes it a difficult phenomenon to study and interpret.

Blazar OJ 287 (z = 0.306) is one of the best observed extragalactic objects. Its historical data base goes back to the 1890's (Sillanpää et al. 1988; Takalo 1994), showing large outbursts with a period of approximately 12 years. Sillanpää et al. (1988) predicted that a new outburst would occur during fall 1994. In order to study and verify this outburst, a large international collaboration was organized: the OJ-94 project (Takalo, Sillanpää, & Kidger 1994; Takalo 1996). During this project we have collected the best-ever observed light curve for any extragalactic object. Our data archive contains over 8000 observations of OJ 287 taken during the last three years (Pursimo & Lehto 1996). The outburst was observed in November 1994, very close to the predicted time (Sillanpää et al. 1996a). During this monitoring, OJ 287 has shown variability, with amplitudes from several magnitudes to tenths of magnitude; in all time scales from tens of minutes to years; during this period no quiescent level was observed. Preliminary searches for microvariability with this data base have been done by Gonzáles-Pérez, Kidger, & de Diego (1994), González-Pérez & Kidger (1996a), González-Pérez et al. (1996b), and Benítez, Dultzin-Hacyan, & Argaiz (1994). They found microvariability during several nights.

Here we present the observational data on OJ 287 taken during an intensive monitoring campaign in January 1994. In § 2 we describe the observations and reduction procedures. A detailed analysis of the data is given in § 3, and finally in § 4 we discuss our results in the frame of various emission mechanisms, scenarios and/or models for the source of the emission.

2. OBSERVATIONS

Observations were made at the Observatorio Astronómico Nacional at San Pedro Mártir (SPM), México —from January 14 to 21 1994— and at the Jacobus Kapteyn Telescope (JKT), and the Nordic Optical Telescope (NOT) at La Palma, Canary Islands from January 12 to 16 1994. The data streams from SPM and JKT overlap on one night, the 14th of January. At SPM we used the 2.1-m telescope with a large format (1024 x 1024) Thomson THX 31156 CCD-chip with metachrome II UV coating and 0.″26 pixel scale, and 10 minutes exposure times throughout the observing run. The observations were taken only in the *V*-band; the observing log is shown in Table 1.

At the one meter JKT we used a (385 x 578) GEC 7 coated CCD-chip with *UBVRIZ* filters and 0.″30 pixel scale. The observing sequence was

TABLE 1

OBSERVING LOG FOR THE SAN PEDRO MARTIR AND LA PALMA OBSERVATIONS

Date (UT)	Number of Hours	Total Number of Images	Telescope	Band
Jan 14	5.5	22	SPM	*V*
Jan 15	4.0	20	SPM	*V*
Jan 16	7.0	24	SPM	*V*
Jan 17	7.0	29	SPM	*V*
Jan 18	3.5	17	SPM	*V*
Jan 19	5.5	24	SPM	*V*
Jan 20	1.5	10	SPM	*V*
Jan 21	5.0	22	SPM	*V*
Jan 12	4.5	62	JKT	*UBVRIZ*
Jan 13	7.0	70	JKT	*UBVRIZ*
Jan 13	4.8	47	NOT	*VRI*
Jan 14	5.5	47	JKT	*UBVRIZ*
Jan 16	4.4	...	NOT	*VRI*

VUVBVRVIVZV... Here the exposure times varied from two to five minutes, depending on the band. The achieved time resolution for the *V*-band was 10 minutes. At the 2.5-m NOT we used a TEK (521 x 512) uncoated CCD (pixel size 0.2″) with *VRI* filters. In this case the observing sequence was *RVRIRVR*... We used 200 second integration times for all bands. This gives a time resolution slightly better than the one obtained with the JKT. Note that on one night (January 13th) the JKT and NOT observations were truly simultaneous. During the last night (January 14th) at the JKT the weather was partly cloudy, so some of these data have quite large errors. Otherwise the typical errors for single measurements were 0.02, 0.02 and 0.01 mag for the SPM, JKT and NOT observations. On one night (January 16th) we used a *UBVRI* polarimeter at the NOT. With this instrument, it is possible to measure polarisation and photometry truly simultaneously in all five colours. For details on the instrument and data reduction see Takalo et al. (1992). An observing log for all the telescopes is shown in Table 1. All the CCD observations were reduced using standard IRAF procedures, including bias subtraction, flat fielding etc. Photometric measurements were made using DAOPHOT in IRAF. For calibration stars we used stars 4, 10, and 11 from the Smith et al. (1985) list.

3. ANALYSIS AND RESULTS

3.1. The Flare

In Figure 1, we show the observed light curves during the flare. The complete OJ-94 project *V*-band light curve can be found in Sillanpää et al. (1994, 1996a,b). From the full light curve it is clear that this flare is typical for OJ 287 . During the observations we detected several similar flares. As can be seen from Figure 1, the flare has a typical synchrotron flare shape, with quite steep increase and shallower decrease. This shape is very similar in all colours. A very interesting feature in this flare is the observed double peak structure. This is best seen in the *V*-band data, where the coverage is more complete. The details are shown in Figure 2. A similar structure can be seen also in the other colour bands (Figure 1). Similar flares have been seen also in 3C66A (Takalo et al. 1996). At the beginning of the flare, OJ 287 brightened 0.50 mag (in *V*-band) in 1.5 days, after that it faded 0.4 mag in 0.8 days, brightened again 0.42 mag in 0.2 days and then faded 0.69 mag in 2.2 days and continued fading after this. The fastest rate of change was 0.08 mag/hr, similar to the one observed by Carini et al. (1992). The observed rest-frame energies involved in these events were 2×10^{40}, 4.13×10^{40}, 1.66×10^{41} and 2.37×10^{40} ergs s^{-1}, respectively, assuming $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$. The rate of the brightness increase was very similar in all five colours during the flare. Also the flare peaked about the same time in all colours. A discrete autocorrelation analysis (Edelson & Krolik 1988; Hugnagel & Bregman 1992) on the observations taken during the flare does not show any clear time delays between the different bands. There is

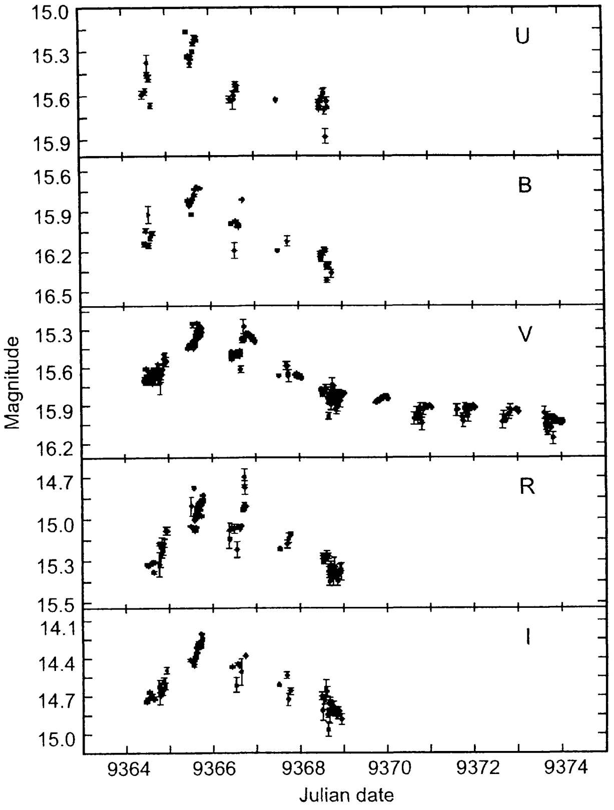

Fig. 1. The observed light curves discussed in the text.

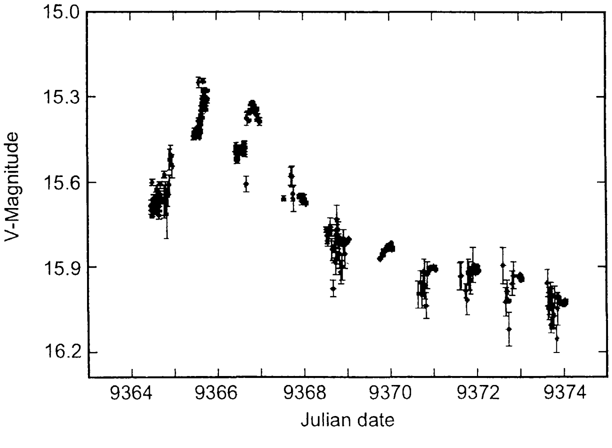

Fig. 2. Details of the flare behaviour in *V*-band.

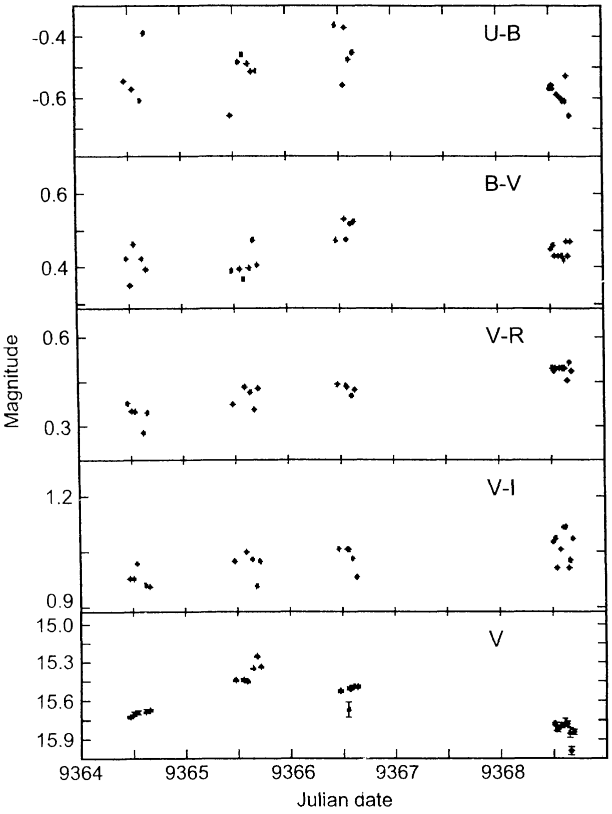

Fig. 3. The observed colour variations during the flare.

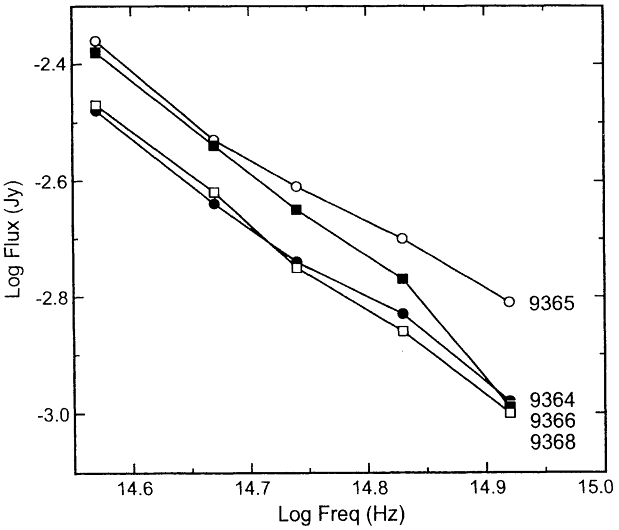

Fig. 4. Examples of the observed spectra.

some indication that the B-band would lead the V and R-bands by about three hours, but this is a very marginal result, and detailed examination of the lightcurves does not to confirm this.

For the JKT and NOT data we have calculated hourly averages of the data in order to search for spectral variations. One problem with this is that the CCD data are not truly simultaneous, although the photopolarimeter data are truly simultaneous. Noticeable colour changes can be seen during the flare. At the begining and the increasing part of the flare, the average $B-V$ colour was 0.42. During the "second" maximum $B-V$ was 0.52, and it stayed there at least a few days (Figure 3). After that we do not have any B-band observations. Similar variations can be seen also in $U-B$ and $V-R$ colours. In the full light curves observed during the OJ-94 project no long term colour variations were detected (Sillanpää et al. 1996c).

We modelled the emission with a power-law ($f_\nu = k\ \nu^\alpha$). The calculated spectral index α varied during the flare. In the beginning of the flare it was -1.42, during the "second" maximum -1.65 and two days afterwards -1.50. Figure 4 shows examples of these spectral variations.

The polarisation also varied during the flare. At the peak the polarisation was about 3% (Efimov & Shakhovskoy 1994). But right after the peak it went up to 7%. During the NOT photopolarimetric observations, the polarisation was only 1%. The position angle varied also from 18 to 80 degrees during this time. These polarisation observations will be discussed elsewhere (Efimov et al. in preparation).

3.2. Microvariability

Usually, microvariability in blazars has been defined as variability with time scales from minutes to hours, and with, up to one magnitude amplitude (for a recent review see Wagner & Witzel 1995). Typically, microvariability lasts a few hours during one or two nights per observing run. In this scenario, for example, the flare increase discussed above would have been called microvariability. Most of the behaviour observed by Carini et al. (1992) can also be described as parts of small flares. In this work, however, we will give a much more rigorous definition of microvariability, namely, we shall consider only the smaller scale variations that occur on top of the overall flare behaviour. The time scales for these oscillations or flickering can be as small as a few minutes. Examples of this microvariability behaviour can be seen in Figures 5 and 6.

In order to quantify the existence of microvariability, straight lines were fitted to the observed differences between the instrumental magnitudes of OJ 287 and the comparison stars, and also to the differences between the magnitudes of two comparison stars. This fitting procedure was done only for the V-band data, since the coverage is best in this band.

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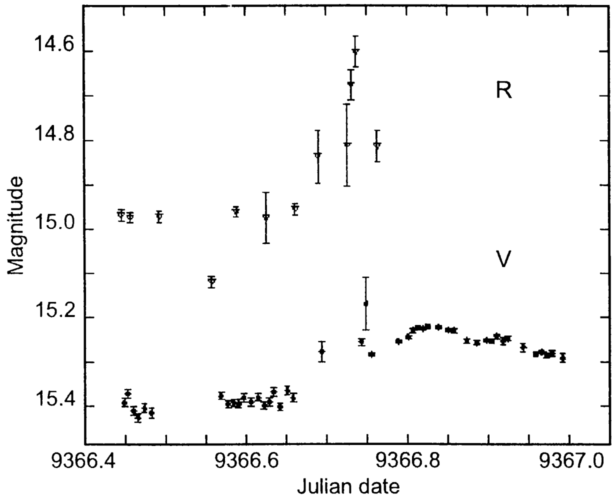

Fig. 5. The microvariability flare seen in V and R-bands on January 14th.

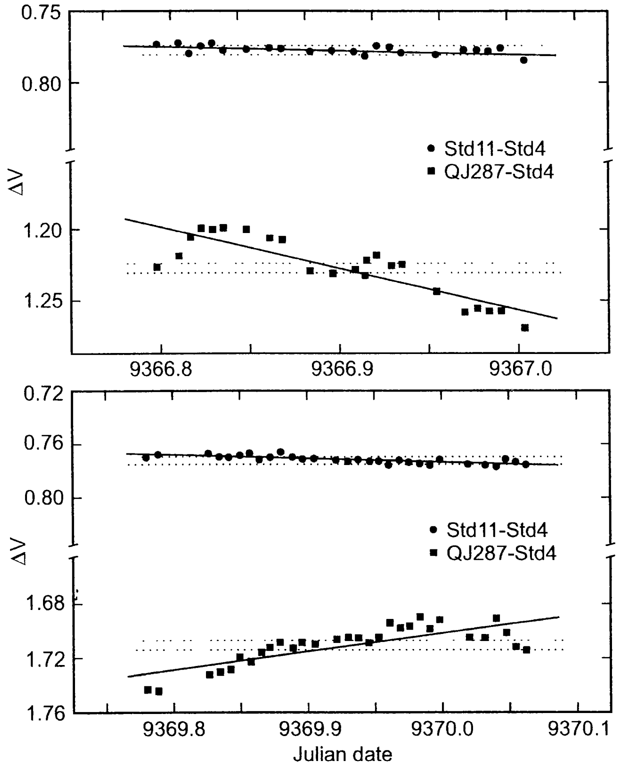

Fig. 6. Examples of the observed microvariability. The straight lines are fits to the data. Dotted lines indicate 2σ errors. In the vertical axis we plot differential instrumental magnitudes.

As a first approach, we looked for the amount of the standard deviations from the line fit to these differences. When the ratio between the fit to OJ 287 *minus* comparison star, and the fit to the difference of the two comparison stars is larger than 3.0, we consider to have observed microvariability. This result was double-checked using the following, more rigorous, approach: The variance for St11-St10 and for OJ-St10 was computed, and the former scaled to account for the difference of brightness between St11 and OJ287, using standard error propagation methods. Finally, an F-test was performed, using the scaled St11-St10 variance (which corresponds to the variance for a non variable source as bright as OJ 287) and the measured OJ-St10 variance. Both methods gave compatible results. However, the F-test method, more precise and suited to detect flickering, also shows the presence of microvariability during nights 15 and 16 January.

In Table 2 we list in the first column the telescope and date of observation; in the second and third columns, the deviations from the line fits to the differential photometry of OJ 287 *minus* star 10, and star 10 *minus* star 11; and finally, in the fourth column we list the ratios of these standard deviations. As can be seen from the table, the first method indicates that microvariability is present in six nights. One drawback with this method for identifying microvariability is that it is not possible to detect small flare-like events with it. Inspection of the nightly light curves shows only one such small flare, on January 14th. This is best seen in the R-band data, where we see a 0.3 mag flare in one hour (Figure 5). There is some indication of this flare also in the V-band; unfortunately, we have no data in the other bands during this time. The SPM V-band data, taken after the JKT data, do not show the flare; instead, there appears small amplitude sinusoidal behaviour (Table 2; Figure 6). All the other microvariability events present have also a smooth sinusoidal character (see Figure 6). The largest amplitudes are 0.05 mag. Typical time scales for these events are of the order of two hours, corresponding to emitting regions smaller than 2.2×10^{14} cm, i.e., about the size of the inner Solar System. These variations resemble damped oscillations, especially during the peak flare. We used the Deeming (1975) method to see if these variations are truly periodic, but no periodicity was found. This is not really surprising, since looking at the light curves it is clear that these variations do not occur every night, and the amplitudes (and perhaps also the time scales), vary from night to night. This erratic behaviour is precisely the characteristic of microvariability.

It is seen from Table 2, that microvariability was more pronounced during the beginning and the peak of the flare, than during the declining phase. Still, microvariability is present also after the flare of January 19th and 21st.

TABLE 2

STANDARD DEVIATIONS FROM THE LINE FITS TO THE DIFFERENTIAL PHOTOMETRIES AND THEIR RATIOS

Telescope/Date	OJ-10	10-11	OJ-10/11-10
JKT 12.1	0.014	0.004	3.5
JKT 13.1	0.023	0.006	3.8
JKT 14.1	0.026	0.015	1.7
SPM 14.1	0.012	0.002	6.0
SPM 15.1	0.006	0.004	1.5
SPM 16.1	0.012	0.006	2.0
SPM 17.1	0.008	0.003	3.0
SPM 18.1	0.004	0.002	2.0
SPM 19.1	0.006	0.002	3.0
SPM 20.1	0.004	0.003	1.3
SPM 21.1	0.007	0.002	3.5

4. DISCUSSION

Flaring seems to be a frequent behaviour in OJ 287 (see Sillanpää et al. 1996a), but microvariability is more rare (e.g., González-Pérez et al. 1996a). During our ten day monitoring in January 1994, we observed one typical synchrotron flare, lasting five days. Most of these microvariability events occurred during the flare.

The double peak in the flare can be due to either an eclipse, or to another flare occurring during the declining part of the first one. The observed colour and spectral changes make the latter explanation more plausible. Also, the shapes of these two flares look identical. Unfortunately, we do not have data taken during the declining part of the first flare. A higher magnetic field could steepen the spectrum during a flare, since the synchrotron losses would then be greater: the upper energy cutoff of the electron distribution is proportional to B^{-2}, so the high-frequency cutoff (or break) in the spectrum varies as B^{-3} (e.g., Kellermann & Owen 1988).

The fact that there is more microvariability during the onset of the flare, quite clearly suggests the occurrence of turbulent events at this time; the possibility that turbulence encountered by shocks can cause microvariability has been pointed out by Marscher, Gear, & Travis (1992). In the declining part of the light curve, microvariability is also seen during small flares, but not during the "smooth" decline from the peak flare. We can identify two types of microvariability events in OJ 287: small sharp flares and smooth sinusoidal variations. The time scales that we observe are one and two hours, respectively. We do not find any periodic variability. There have been previous claims of periodic short term variations in OJ 287, with periods in the range of tens of minutes (Takalo 1994 and references therein).

These observations have clearly shown that the emission processes in OJ 287 are very complex, and that there are probably several —at least three— different emission mechanisms overlapped: one related to the underlying steady emission, another one responsible for the synchrotron flares, and still other(s) responsible for the microvariability. The steady emission is most likely associated with the emission from the underlying galaxy (Benítez et al. 1996), the bulk of the accretion disk, and the steady synchrotron emission in the jet. The flare emission can be caused by (at least) two different mechanisms and emission locations: a) small outbursts in the inner accretion disk (Abramowicz et al. 1992; Wiita et al. 1992); b) shocks propagating along the jet (e.g., Marscher et al. 1992). Both types of instabilities are probably induced by variations in the accretion rate. Even more localized, and probably enhanced instabilities (e.g., Lesch & Pohl 1992) can produced the observed smaller scale microvariability. Microlensing effects (e.g., Ostriker & Vietri 1985) have been invoked also as a possible cause of microvariability.

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