Astron. Astrophys. 364, 450–454 (2000)

ASTRONOMY AND ASTROPHYSICS

TeV observations of PKS 2005-489 and PKS 0548-322

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Received 22 May 2000 / Accepted 23 October 2000

Abstract. Observations have been made using the University of Durham Mark 6 telescope of the nearby X-ray selected BL Lacs PKS 2005–489 and PKS 0548–322 which should be strong candidates as sources of TeV emission. We find no evidence for long-term emission of VHE gamma rays from these sources in extended measurements covering ~ 2 years. We find $3\ \sigma$ limits to the VHE gamma ray flux of $0.79 \times 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ above 400 GeV for PKS 2005–489 and $2.4 \times 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ above 300 GeV for PKS 0548–322.

Key words: galaxies: BL Lacertae objects: general – gamma rays: observations

1. Introduction

The detection of very high energy (VHE) gamma rays from at least 5 high energy cut-off BL Lacs (HBLs) has emphasised the importance of such studies, both to help understand the physics of jets in AGNs and as a probe of the infra-red background. The VHE sources detected to date include Mrk 421 (Punch et al. 1992, Petry et al. 1996), Mrk 501 (Quinn et al. 1996, Bradbury et al. 1997), 1ES 2344+514 (Catanese et al. 1998), PKS 2155–304 (Chadwick et al. 1999) and 1ES 1959+650 (Nishiyama et al. 1999). All these sources are characterised by being comparatively close and exhibit a peak in the X-ray region of the spectrum. The VHE emission from these objects has been highly variable, with flaring activity observed on timescales as short as 30 minutes and correlated with the activity at other wavelengths (e.g. Gaidos et al. 1996, Buckley et al. 1996, Quinn et al. 1999).

PKS 0548–322 and PKS 2005–489 are the closest Southern hemisphere HBLs. Stecker et al. (1996) have predicted VHE gamma ray fluxes from these objects, based on a simple model relating the X-ray flux to the gamma ray flux and taking into account the expected absorption on the IR background. These predictions confirm that PKS 0548–322 and PKS 2005–489 are strong candidates for detection as VHE emitters with the current generation of telescopes.

PKS 2005–489 was identified as a very bright BL Lac by Wall et al. 1986 and was found to be at a distance of $z = 0.071$ (Falomo et al. 1987). Although it was discovered in the radio-band (and so would formerly have been classified as a radio-selected BL Lac) it is now classified as an HBL or an intermediate object on the basis of its X-ray-to-radio flux ratio (Sambruna et al. 1995, Perlman et al. 1996). Unusually, it has been detected in the EUV band (Marshall et al. 1995). Although not listed as a 100 MeV gamma ray source in the 2nd or 3rd EGRET catalogues (Thompson et al. 1995, Hartman et al. 1999) it is seen as a marginal source at energies above 100 MeV (Lin et al. 1996, Lin et al. 1997, Lin et al. 1999). It also seen at marginal significance in the GeV EGRET catalogue (Lamb & Macomb 1997).

PKS 0548–322 is another very bright BL Lac at a similar distance of $z = 0.069$ (Fosbury & Disney 1976). The high X-ray flux and wide band spectral shape indicates that it is a HBL. Observations with OSSE (McNaron-Brown et al. 1995) and EGRET (Thompson et al. 1995, Hartman et al. 1999) have failed to detect gamma ray emission.

The CANGAROO group have reported limits to VHE gamma ray emission above $\sim\ 1.5$ TeV for PKS 0548–322 (Roberts et al. 1999) and for PKS 2005–489 (Roberts et al. 1998, Roberts et al. 1999). We have extended the VHE coverage of these objects down to ~ 300 GeV using extensive observations made with the University of Durham Mark 6 gamma ray telescope at Narrabri, NSW, Australia from 1996 to 1998. The results of these observations are reported, including those taken during a multiwavelength campaign on PKS 2005–489 (Perlman et al. 1999).

2. Observations

VHE gamma ray observations were made with the Mark 6 telescope (Armstrong et al. 1999) on clear moonless nights. The telescope has an energy threshold of about 300 GeV for observations at the zenith. Data were taken in our normal off-on-on-off mode where a half-hour on-source observation is bracketed by two 15-minute off-source observations which are at the source position displaced by ± 15 minutes in RA. Data were subjected

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to our normal quality control procedures and processed following the criteria used for our detection of VHE emission from PKS 2155–304 (Chadwick et al. 1999).

After quality control, our dataset for PKS 0548–322 consists of 105 fifteen minute on-source segments spread over 23 nights of observation. The dataset for PKS 2005–489 consists of 280 on-source fifteen minute data segments spread over 58 nights. An observation log is given in Table A.1. The PKS 2005–489 data in 1998 October were taken during a multiwavelength campaign.

3. Results

3.1. Limits on longterm emission

The dataset for each source has been tested for the presence of gamma ray signals. We find 3 σ flux limits, based on the maximum likelihood ratio test (Gibson et al. 1982, Li & Ma 1983), of $0.79 \times 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ above 400 GeV for PKS 2005–489 and $2.4 \times 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ above 300 GeV for PKS 0548–322. The threshold energy, defined as the peak of the differential triggering spectrum, for the observations has been estimated on the basis of preliminary simulations, and is in the range 300 to 400 GeV for these objects, depending on the object's elevation. The effective collecting areas which have been assumed, again from simulations, are $5.5 \times 10^8\ \mathrm{cm}^2$ at an energy threshold of 300 GeV and $1.0 \times 10^9\ \mathrm{cm}^2$ at an energy threshold of 400 GeV. These are subject to systematic errors estimated to be $\sim 50\%$. We have assumed that our current selection procedures retain $\sim 20\%$ of the γ-ray signal, which is subject to a systematic error of $\sim$ 60%. The preliminary simulations have assumed a source spectrum similar to the cosmic ray spectrum. Deviations from this assumption change the limits found by amounts that are small compared with the systematic errors. A detailed analysis of the spectral response of the Mark 6 telescope awaits the completion of more detailed simulations, which are in progress.

3.2. Search for short bursts

We have subdivided our data sets on two timescales, a dark period of about 2 weeks and on a night-by-night basis, to look for evidence for emission. Following the procedure we have adopted for our analysis of data from PKS 2155–304 (Chadwick et al. 1999), we have normalised our data by dividing the gamma ray excess by the number of off-source hadron initiated showers which survive the cuts.

In Fig. 1 we show the results of such an analysis of our PKS 2005–489 data. We show the normalised excesses binned by dark period (Fig. 1a) and by day (Fig. 1b). We also show a histogram of the day-by-day significances for gamma ray emission (Fig. 1c). These data show no evidence for variable emission on time scales of a dark period or a day. However, it is interesting to note that the distribution of excesses shows 2 nights with excesses in the 2.75 – 3.25 σ band where none is expected.

In Fig. 2 we show the results of a similar analysis of data from PKS0548–322. Again we conclude that there is no evidence for variable emission on time scales of weeks or days.

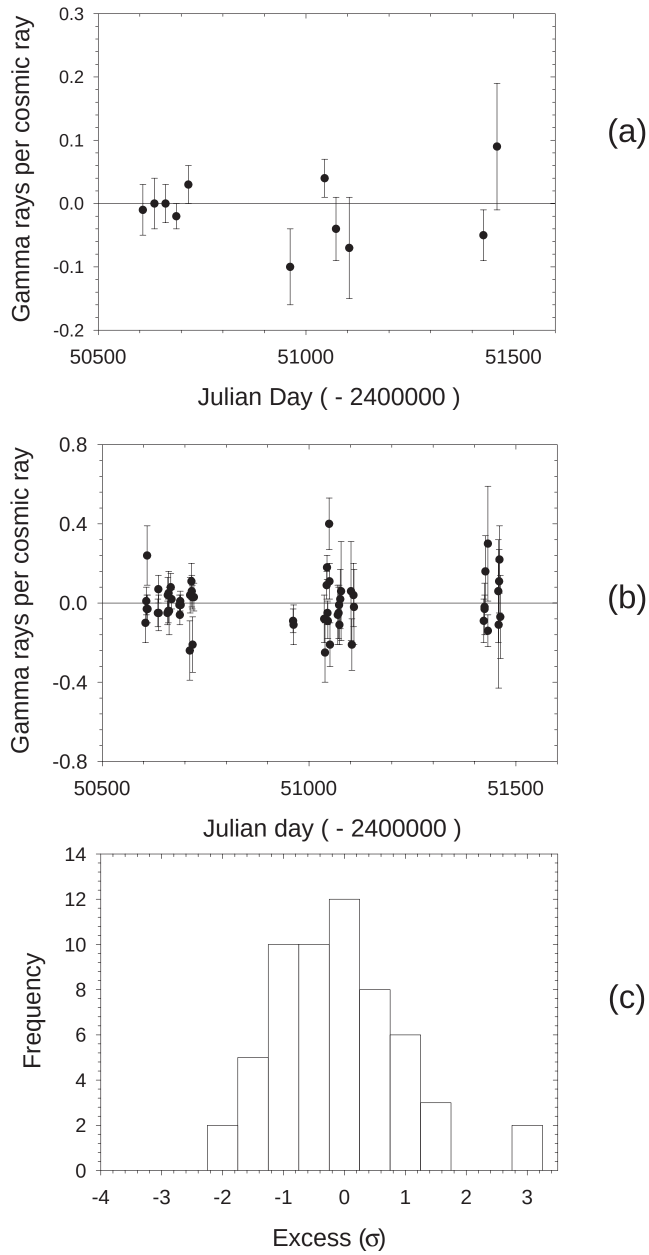

Fig. 1a–c. The time variation of the measured VHE gamma ray signal from PKS 2005-489. **a** shows the time variation of the detected gamma ray signal strength (in units of gamma rays per cosmic ray – see text) averaged over dark periods. **b** shows the time variation of the detected gamma ray signal on a nightly basis while **c** shows the distribution of these excesses.

3.3. The November 1998 PKS 2005–489 X-ray flare

A multiwavelength campaign on PKS 2005–489 occurred during 1998 September and October. The results of this are due to be reported elswhere (Perlman et al. 2000). During this period there was a large X-ray flare from PKS 2005–489 which lasted until 1998 December (Remillard 1998, Perlman et al. 1999). At its peak, on 1998 November 10, the 2–10 keV X-ray flux was about 30 times brighter than in its quiescent state (Perlman et al. 1999). VHE observations were made with the

Table 1. Limits (3σ) to VHE emission from PKS 2005–489 during the 1998 flare. The X-ray measuements are from the *RXTE* observations of Perlman et al. (1999).

Date	VHE gamma ray flux limit ($\times 10^{-10}\,\mathrm{cm^{-2}\,s^{-1}}$)	X-ray flux (2–10 keV) ($\times 10^{-10}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$)
1998 October 15	0.9	16.78
1998 October 17	0.7	–
1998 October 21	2.6	16.37
1998 October 22	2.3	15.40

Mark 6 telescope at all times when weather conditions and the moon phase permitted during 1998 October. During 1998 November and December, PKS 2005–489 was at too large a zenith angle for meaningful observations to be made.

VHE observations were available for 1998 October 15, 17, 21 and 22. The daily VHE limits, together with the X-ray rates (from Perlman et al. 1999) are shown in Table 1. There is no indication of VHE emission at the sensitivities achievable with the Mark 6 telescope during this flare.

4. Discussion

There is a broad understanding of the processes in blazars that give rise to the high energy component that is seen. Current models ascribe this high energy emission to production by inverse Compton scattering of low energy photons by the relativistic jet. These soft photons may be either the synchrotron photons themselves (the SSC model) or photons produced in the disc or broad line region.

The peak frequency of this Compton component is then determined by the position of the lower energy synchrotron peak. A simple model has recently been introduced to account for the phenomenology of gamma-ray bright blazars (Fossati et al. 1998, Ghisellini et al. 1998). This model predicts that

- there is a fixed ratio between the frequencies of the Compton and synchrotron energy peaks of 5×10^8
- the high energy peak luminosity and the radio luminosity (at 5 GHz) have a fixed ratio of 3×10^3.

Stecker et al. (1996) have made predictions of the VHE flux from these objects, using a simple model for the VHE emission and taking into account absorption on the IR background. They use simple arguments to relate the VHE fluxes to the X-ray flux, assuming that the emission is similar to that observed for Mrk 421.

It should be emphasised that the models of Fossati et al. (1998), Ghisellini et al. (1998) and Stecker et al. (1996) are descriptive of classes of blazars, but do not provide accurate predictions for individual objects. Naturally, the models are consistent with the detailed TeV spectra available for Mrk 421 and Mrk 501, but it is far from clear that all blazars can be fully characterized by the synchrotron luminosity and peak energy flux frequency alone. A further caveat when using descriptive models to predict the flux for an individual object arises from the fact that the compiled SEDs are not derived from simultaneous measurements and may be subject to significant observing biases. Many EGRET blazars are only seen in outburst, whereas the radio measurements may be dominated by quiescent emission. Even with these reservations, it is still helpful to consider the order of magnitude predictions generated by applying these models to these objects.

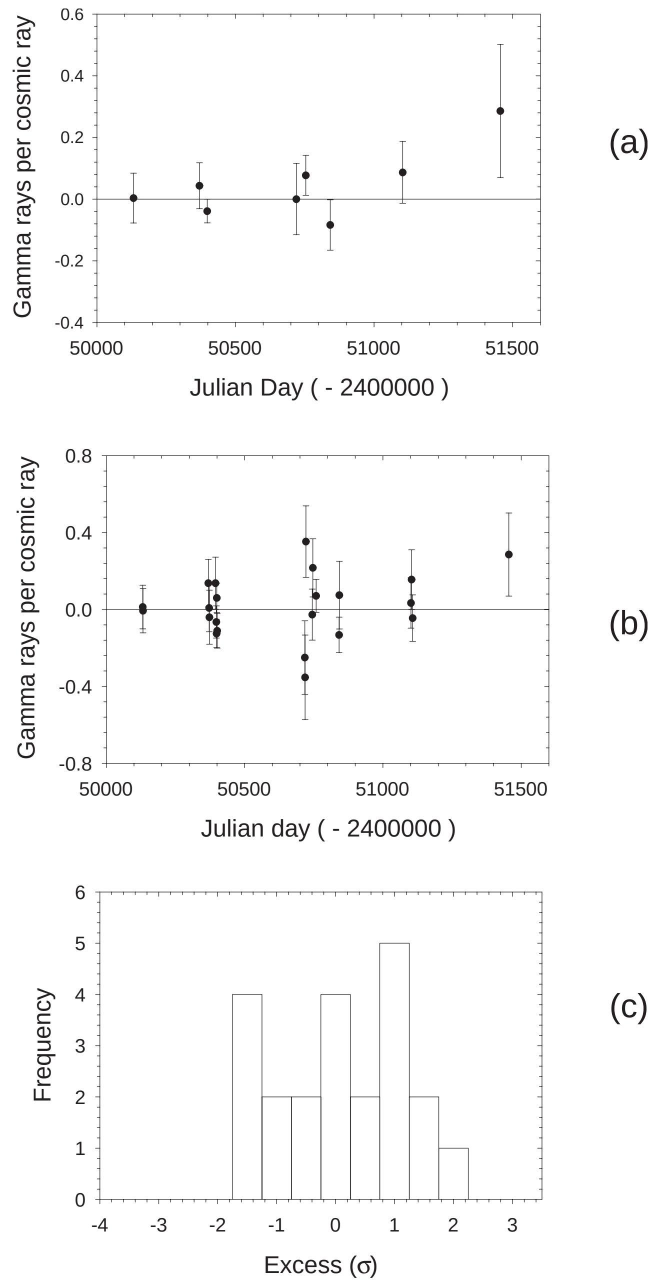

Fig. 2a–c. The time variation of the measured VHE gamma ray signal from PKS 0548–322. The information displayed is as for Fig. 1.

PKS 2005–489 shows very different temporal behaviour in outburst to that of either Mrk 421 or Mrk 501. The latter two objects both show short timescale ($\sim$ 15 min) variations, whereas

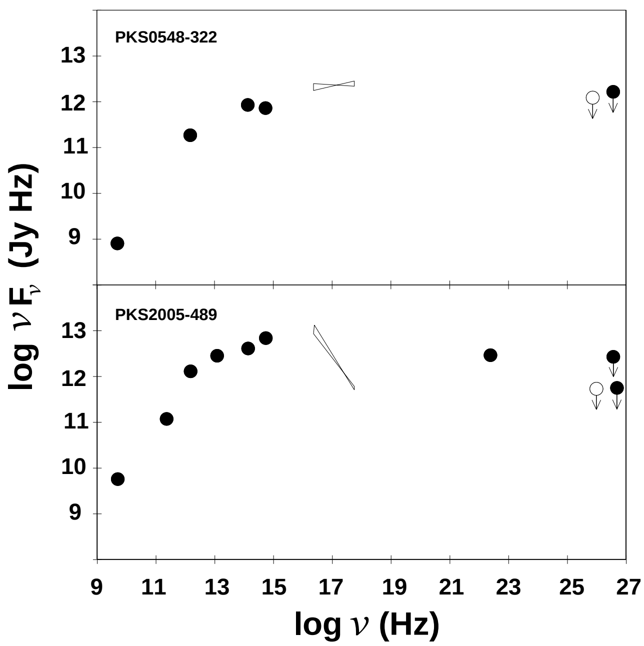

Fig. 3. The broadband spectral energy distributions for PKS 0548–322 and PKS 2005-489. The datapoints denoted by • are from the compilation of Fossati et al. (1998) with the addition of VHE data from Roberts et al. (1999); points from the present work are denoted by ○. Measurements are not simultaneous. The EGRET measurement for PKS 2005–489 is a $\sim 4\sigma$ detection from the first source catalogue (Fichtel et al. 1994). The appropriate error bars are similar to the size of the symbol used.
All flux limits shown in this figure are 2σ.

the X-ray light curve of PKS 2005–489 during the 1998 outburst shows no evidence for any such variations. This suggests that a detailed model of this particular object must invoke factors that explain this difference and which may also affect the TeV emission. The VHE observations ended well before the peak of the outburst, so the upper limits given do not constrain correlation models as strongly as would be the case if the outburst had occurred three weeks earlier. Further VHE observations, even at the same sensitivity, would therefore be useful in the context of a multi-wavelength campaign.

In Fig. 3 we show the broadband spectral energy distributions (SEDs) for PKS 2005–489 and PKS 0548–322. Data points at other wavelengths are taken from the compilation of Fossati et al. (1998) which are obtained by averaging all available data in wavelength bands. In plotting points from the present work we assume a spectral index of -1.6. Since our VHE points are derived from exposures over a period of ~ 2 years, it is appropriate to add our data to these compilations. We note that our new limits to VHE emission provide a much stronger constraint to the SEDs than previously reported results.

We can use these SEDs to test whether our measurements suggest that these objects conform to the predictions of the model of Fossati et al. (1998). For PKS 0548–322, the synchrotron peak is seen to occur at a frequency of $\geq 10^{17.5}$ Hz. This in turn implies that the Compton peak should occur at $\geq 1.5 \times 10^{26}$ Hz or ≥ 0.6 TeV. The radio flux at 5 GHz is measured to be $\sim 1.2 \times 10^{-14}$ erg cm^{-2} s^{-1} (Kuhr et al. 1981, Stickel et al. 1991, Giommi et al. 1995) which leads to an expected flux at the Compton peak (0.6 TeV) of 3.6×10^{-11} cm^{-2} s^{-1}.

Similarly, for PKS 2005–489, the SED (Fig. 3) indicates that the synchrotron peak occurs at about 10^{16} Hz. The model of Fossati et al. 1998 then predicts that the Compton peak will occur at about 5×10^{24} Hz, i.e. ~ 20 GeV. The radio flux at 5 GHz is measured to be 6.05×10^{-14} erg cm^{-2} s^{-1} (Sambruna et al. 1996) which leads to an expected flux at the Compton peak (20 GeV) of 1.8×10^{-10} cm^{-2} s^{-1}. Neither of these predictions is in conflict with the limits to VHE emission from these objects.

Using the Stecker et al. (1996) model we predict values of 0.51×10^{-11} cm^{-2} s^{-1} for the VHE flux from PKS 2005–489 and 1.3×10^{-11} cm^{-2} s^{-1} for PKS 0548–322. Our experimental upper limits are not in conflict with these predictions.

Using an inhomogeneous jet model (due to Ghisellini et al. 1985) Sambruna et al. (1996) have modelled the expected VHE flux from PKS 2005–489. They predict a sharp cut-off in the Compton peak at about 100 GeV. Again, this is not in conflict with the present results.

5. Conclusions

Extensive monitoring of the HBLs PKS 0548–322 and PKS 2005–489 over the lifetime of the University of Durham Mark 6 telescope has failed to provide any evidence for VHE gamma ray emission. However, the predicted VHE fluxes using the models of Stecker et al. (1996) and Fossati et al. (1998) are not in conflict with the present flux limits. These objects should be readily detectable in the VHE band when the next generation of Southern hemisphere ACTs become operational.

The broad-band spectral energy distributions of these two objects are not as well sampled as those of Mrk 501 and Mrk 421. In spite of this, we observe that the broad-band spectral energy distributions for PKS 0548–322 and PKS 2005–489 compiled here bear a resemblance to those compiled for Mrk 501 and Mrk 421, respectively (e.g. Kubo et al. 1998). PKS 0548–322 shows a broader, higher energy synchrotron peak than PKS 2005–489, which is similar to the comparison between Mrk 501 and Mrk 421.

Mrk 501 and Mrk 421 are both at the same distance ($z = 0.031$) but show different VHE spectral shapes (Krennrich et al. 1999). Thus, the different VHE spectral shapes must be due to variation in the intrinsic source spectrum and so the effects of gamma ray absorption on the IR background cannot be determined. Studies of the VHE spectra from PKS 0548–322 and PKS 2005–489 (which are both at $z \sim 0.07$) with the new generation of Southern hemisphere ACT arrays (HESS and CANGAROO III) hold out the prospect of separating the effects of source spectrum variation and IR absorption. We suggest that these objects should be a high-priority targets when these new VHE facilties become operational in 2001 – 2002.

Acknowledgements. We are grateful to the UK Particle Physics and Astronomy Research Council for support of the project. The Mark 6 telescope was constructed with the assistance of the staff of the Physics Department, University of Durham, and the efforts of Mr. P. Cottle, Mrs. E.S. Hilton and Mr. K. Tindale are acknowledged with gratitude.

We would like to thank the anonymous referee for helpful comments.

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Appendix A: observing log

Table A.1. Observing log for observations of PKS 0548-322 and PKS 2005-489 made with the Mark 6 Telescope.

PKS 2005-489	
Date	No. of ON source scans
1997 June 5	3
1997 June 7	5
1997 June 8	5
1997 June 9	2
1997 June 10	5
1997 July 5	7
1997 July 6	8
1997 July 7	5
1997 July 28	8
1997 July 29	6
1997 July 30	10
1997 July 31	2
1997 August 1	2
1997 August 5	9
1997 August 7	10
1997 August 26	10
1997 August 27	9
1997 August 28	10
1997 August 29	9
1997 September 20	2
1997 September 21	3
1997 September 24	5
1997 September 25	7
1997 September 26	6
1997 September 27	2
1997 September 30	6
1998 May 28	7
1998 May 29	4
1998 August 11	2
1998 August 13	2
1998 August 17	7
1998 August 18	9
1998 August 19	9
1998 August 20	4
1998 August 23	5
1998 August 24	7
1998 August 25	3
1998 September 13	6
1998 September 15	4
1998 September 16	7
1998 September 17	4
1998 September 19	4
1998 September 21	1
1998 October 15	2
1998 October 17	4
1998 October 21	1
1998 October 22	1
1999 September 1	3
1999 September 3	8
1999 September 4	1
1999 September 5	1
1999 September 11	7
1999 October 4	1
1999 October 6	2
1999 October 7	1
1999 October 8	2
1999 October 9	3
1999 October 11	2

PKS 0548-322	
Date	No. of ON source scans
1996 February 18	4
1996 February 19	4
1996 October 12	7
1996 October 15	2
1996 October 16	3
1996 November 7	6
1996 November 10	5
1996 November 11	8
1996 November 12	8
1996 November 13	6
1997 September 25	1
1997 September 26	3
1997 September 27	2
1997 September 30	6
1997 October 23	2
1997 October 25	2
1997 November 6	7
1998 January 28	7
1998 January 29	4
1998 October 15	6
1998 October 17	7
1998 October 21	3
1999 October 4	2