The physical parameters of Markarian 501 during flaring activity

W. Bednarek and R. J. Protheroe

1Department of Physics and Mathematical Physics, The University of Adelaide, Adelaide, Australia 5005
2University of Łódź, ul. Pomorska 149/153, 90-236 Łódź, Poland

Accepted 1999 May 19. Received 1999 May 6; in original form 1999 February 8

ABSTRACT

We determine the physical parameters (magnetic field and Doppler factor) of the homogeneous synchrotron self-Compton model allowed by the observed X-ray to gamma-ray spectra and variability of Markarian 501 during the 1997 April 15–16 flaring activity. We find that magnetic fields between 0.07 and 0.6 G and Doppler factors between 12 and 36 could fit (depending on observed variability time-scale) these observations. We take account of photon–photon pair production interactions of gamma-ray photons occurring both inside the emission region and during propagation to Earth, and find these to be extremely important in correctly determining the allowed model parameters. Previous estimates of the allowed parameter space have neglected this effect. Future multiwavelength campaigns during strong flaring activity, including observations from optical to TeV gamma-rays, should enable the physical parameters to be further constrained.

Key words: radiation mechanisms: non-thermal – galaxies: active – galaxies: individual: Mrk 501 – galaxies: jets.

1 INTRODUCTION

Four BL Lac objects have been detected in the TeV energy range: Mrk 421 (Punch et al. 1992), Mrk 501 (Quinn et al. 1996), 1ES 2344+514 (Catanese et al. 1998), and PKS 2155–304 (Chadwick et al. 1999). In two of these, Mrk 421 and 501, the high level of γ-ray emission enabled the spectrum to be measured up to ∼10 TeV (Aharonian et al. 1997; Zweerink et al. 1997; Djannati-Atai et al. 1998; Hayashida et al. 1998; Samuelson et al. 1998). In the case of Mrk 421, the spectrum can be adequately described by a single power law between 0.3 and 10 TeV. However, the spectrum of Mrk 501 shows clear curvature over a similar energy range (Krennrich 1999). Recently, the spectrum of Mrk 501 has been measured up to 24 TeV by the HEGRA telescopes (Konopelko et al. 1999; Krawczynski et al. 1999).

The γ-ray emission of these two BL Lacs shows very rapid variability. For Mrk 421, variability on a time-scale as short as ∼15 min has been reported (Gaidos et al. 1996). In the case of Mrk 501, variability on a time-scale of a few hours was observed during the 1997 high level of activity (Aharonian et al. 1999; Quinn et al. 1999), and there is some evidence of variability on a time-scale of 20 min (Aharonian et al. 1998).

The TeV γ-ray flares are simultaneous with the X-ray flares. In the case of Mrk 501, during the 1997 April 16 flare the X-ray spectrum was observed by the Beppo-SAX observatory up to ∼200 keV (Pian et al. 1998), and during the same high state OSSE observations made in 1997 April 9–15 (Catanese et al. 1997) show that the energy flux per log energy interval continues up to ∼500 keV at roughly the same level.

Gamma-ray emission from active galactic nuclei (AGN) is often interpreted in terms of the homogeneous ‘synchrotron self-Compton model’ (SSC) in which the low-energy emission (from radio to X-rays) is synchrotron radiation produced by electrons which also up-scatter these low-energy photons into high-energy γ-rays by inverse Compton scattering (ICS) (Macomb et al. 1995; Bloom & Marscher 1996; Inoue & Takahara 1996; Mastichiadis & Kirk 1997). In this model all the radiation comes from this same region in the jet. Such a picture can naturally explain synchronized variability at different photon energies.

The inclusion of photon–photon pair production interactions of γ-rays with low-energy radiation within the emission region has been used previously when constraining the physical parameters of blazars (e.g. Mattox et al. 1993; Dondi & Ghisellini 1995). This was also included in our previous paper (Bednarek & Protheroe 1997), where we constrained the allowed parameter space of the homogeneous SSC model, i.e., the magnetic field in the emission region and the Doppler factor, based on observations of the 1994 flaring activity in Mrk 421. More recently, a similar analysis has been performed for Mrk 501 by various authors (Tavecchio, Maraschi & Ghisellini 1998; Kataoka et al. 1999). However, in this recent work, absorption on both the infrared background (IRB) and the internal radiation of the emission region has been neglected. In the present paper we show that inclusion of both these effects is vital in order to determine the allowed parameter space properly.
In Section 2 we discuss the effect of photon–photon pair production interactions of γ-rays with synchrotron radiation produced inside the emission region, and with IRB photons during propagation to Earth. In Section 3 we obtain the values of \(B\) and \(D\) allowed by the observed ratio of γ-ray to X-ray power, and in Section 4 we discuss additional constraints arising from the requirement that the radiative cooling time must be consistent with the observed variability time-scale. In Section 5 we further narrow down the allowed model parameters by comparing the predicted TeV γ-ray spectrum with that observed, and finally we discuss the implications of our results.

2 ABSORPTION OF GAMMA-RAYS BY PHOTON–PHOTON PAIR PRODUCTION

For propagation of γ-rays through isotropic radiation the reciprocal of the mean interaction length for photon–photon pair production is given by

\[
x_{\gamma\gamma}(E_\gamma)^{-1} = \frac{1}{8E_\gamma^2} \int_{s_{\text{min}}}^{s_{\text{max}}} \frac{d\sigma}{d\omega} \frac{n(\varepsilon)}{\varepsilon^2} \varepsilon_{\text{max}}(\varepsilon, E_\gamma) \int s_{\text{min}} s_{\text{max}} ds \sigma(s),
\]

where \(n(\varepsilon)\) is the differential photon number density, and \(\sigma(s)\) is the total cross-section for photon–photon pair production (Jauch & Rohrlich 1955) for a centre of momentum frame energy squared given by \(s = 2\varepsilon E_\gamma(1 - \cos \theta)\), where \(\theta\) is the angle between the directions of the energetic photon and soft photon, and \(s_{\text{min}} = (2m_c^2)^2, s_{\text{min}} = (2m_c^2)^2/4E_\gamma, \text{and } s_{\text{max}}(\varepsilon, E_\gamma) = 4\varepsilon E_\gamma\).

We shall now apply these formulae directly to obtain the mean interaction length in the IRB and, in a modified form, to obtain the optical depth in the synchrotron radiation produced in the emission region.

2.1 Absorption of gamma-rays in the infrared background

The spectra of γ-rays from extragalactic objects are modified by photon–photon pair production interactions with the infrared background, and observations of the γ-ray spectra of Mrk 421 and 501 have been used to constrain the intensity of the IRB (Biller et al. 1998; Stanek & Franceschini 1998). Recently, Malkan & Stecker (1998) have modelled the IRB by summing the contributions from different types of galaxy taking account of evolution. We use their upper and lower models which are consistent with recent COBE DIRBE data (Hauser et al. 1998) and COBE FIRAS data (Fixsen et al. 1998), which we use to extend the model of Malkan & Stecker down below 3 μm.

We obtain the mean interaction length, \(x_{\gamma\gamma}(E_\gamma)\), in the IRB plus cosmic microwave background radiation (CMBR), and these are shown in Fig. 1(a). We also show separately the mean free path in the CMBR alone. Our results are in good agreement with those of Stecker & De Jager (1998) calculated for the same IRB models (see Stecker & De Jager for references to earlier work). In Fig. 1(b) we show the reduction factor, \(R(E_\gamma) = \exp(-\tau_{\text{IR}}(E_\gamma)) = \exp[-d/x_{\gamma\gamma}(E_\gamma)\) for a source distance of \(d = 202\) Mpc obtained for Mrk 501 assuming \(H_0 = 50\) km s\(^{-1}\) Mpc\(^{-1}\) and a redshift of \(z = 0.033\). Clearly, absorption in the IRB becomes very important above 400 GeV. Fig. 2 shows the 1997 April 15–16 HEGRA and CAT data, together with the approximation used later in this paper for the high-energy part of the spectral energy distribution (SED). The figure also shows this SED after correction for absorption in the infrared using the two reduction factors of Fig. 1(b).

2.2 Absorption of gamma-rays in the blob radiation

Absorption of γ-rays will also take place on the synchrotron photons produced inside the emission region. For the spectrum of these target photons we use a fit to the Beppo-SAX observations made during the April 15/16 flaring activity (Pian et al. 1998), together with an indication from OSSE observations made during the high state in 1997 April (Cataneo et al. 1997) that the spectrum continued to \(E_{\gamma,\text{max}} = 500\) keV with approximately the same energy flux per log energy interval. The differential photon flux in the optical to X-ray region observed from Mrk 501 during the 1997 April 16 flare (photon cm\(^{-2}\) s\(^{-1}\) GeV\(^{-1}\)) is approximated by

\[
F(\varepsilon) \approx \begin{cases} 
3 \times 10^{-4} \varepsilon^{-1.4} & \varepsilon \leq \varepsilon_{\gamma,1} = 2.14 \times 10^{-6} \text{ GeV}, \\
2.5 \times 10^{-5} \varepsilon^{-1.59} & \varepsilon_{\gamma,1} < \varepsilon \leq \varepsilon_{\gamma,2} = 1.95 \times 10^{-5} \text{ GeV}, \\
1.86 \times 10^{-6} \varepsilon^{-1.83} & \varepsilon_{\gamma,2} < \varepsilon \leq \varepsilon_{\gamma,3} = 2 \times 10^{-4} \text{ GeV}, \\
4.37 \times 10^{-7} \varepsilon^{-2} & \varepsilon_{\gamma,3} < \varepsilon \leq E_{\gamma,\text{max}}.
\end{cases}
\]

The photon density in the emission region depends on the
The spectrum of Mrk 501 shows two clear bumps which, during the outburst stage, extend up to at least ~500 keV (Catanese et al. 1997; Pian et al. 1998), and up to at least ~10 TeV (Aharonian et al. 1997; Djannati-Atai et al. 1998; Hayashida et al. 1998; Krennrich et al. 1999; see also Protheroe et al. 1998 for a review), the highest energy of γ-rays observed being 24 TeV (Konopelko et al. 1999; Krawczynski et al. 1999). These multiwavelength observations of Mrk 501 allow us to define the ratio \( \eta \) of the energy flux per log energy interval observed at a chosen γ-ray energy, \( E_* = 1 \) TeV, at which the emission is assumed to be due to Compton scattering, to that at a chosen X-ray energy, \( \varepsilon = 2 \) keV, at which the emission is assumed to be due to synchrotron radiation,

\[
\eta = \left( \frac{dN}{dE_\gamma \, d\varepsilon} \right)_{E_*} E_*^2 e^{-\tau_{\text{tot}}(E_\gamma)} \left( \frac{dN}{dE_\gamma \, d\varepsilon} \right)_{\varepsilon} e^{\tau_{\text{tot}}(E_\gamma)}.
\]

where \( \tau_{\text{tot}}(E_\gamma) = \tau_{\text{syn}}(E_\gamma) + \tau_{\text{abs}}(E_\gamma) \) is the total optical depth for photons in the synchrotron radiation of the blob and the infrared–microwave background, and the primed quantities are measured in the blob frame. For the power at γ-ray energies we adopt the value reported by the CAT experiment at \( E_* = 1 \) TeV (Djannati-Atai et al. 1998), and for the power at X-ray synchrotron energies we take the value at \( \varepsilon = 2 \) keV (Pian et al. 1998). For these two energies \( \eta \approx 3.6 \), and from this constraint we shall now obtain the required magnetic field as a function of the Doppler factor for various variability time-scales.

The synchrotron spectrum at \( \varepsilon' \) in the above formula (equation 7) can be approximated analytically by

\[
\varepsilon' \frac{dN}{d\varepsilon'} d\varepsilon' \approx \frac{dN}{d\gamma'} d\gamma' b_{\text{syn}}(\gamma'),
\]

where \( dN/d\gamma' \) is the electron spectrum in the blob rest frame. \( b_{\text{syn}}(\gamma') = kU_B \gamma'^2 \) is the energy loss rate of electrons, where \( k = 4c\sigma_T/3 \), \( \sigma_T \) is the Thomson cross-section, and \( U_B \) is the magnetic field energy density. The characteristic energy of synchrotron photons is given by

\[
\varepsilon' \approx 0.5E_B\gamma^2.
\]

We use the observed low-energy SED (equation 2) to estimate the blob-frame equilibrium electron spectrum

\[
\frac{dN}{d\gamma'} = \begin{cases} 
   a_1 \gamma'^{-1.8} & \gamma' \leq \gamma_{b,1}, \\
   a_2 \gamma'^{-2.18} & \gamma_{b,1} < \gamma' \leq \gamma_{b,2}, \\
   a_3 \gamma'^{-2.66} & \gamma_{b,2} < \gamma' \leq \gamma_{b,3}, \\
   a_4 \gamma'^{-3} & \gamma_{b,3} < \gamma' \leq \gamma_{b,\text{max}},
\end{cases}
\]

where \( \gamma' \) is the Lorentz factor in the blob frame,

\[
\gamma_{b,n} = \left( 2\rho_{b,n}/E_B \right)^{1/2},
\]

where \( n = 1, 2, 3 \), and \( a_1 = \gamma_{b,1}^{-0.38} \), \( a_2 = 1 \), \( a_3 = \gamma_{b,3}^{0.48} \), \( a_4 = a_3 \gamma_{b,3}^{0.4} \), \( \rho_B = m_e c^2 B/B_{\text{crit}} \), \( B_{\text{crit}} = 4.41 \times 10^{13} \text{ G} \), and \( m_e \) is the electron rest mass.

The synchrotron spectrum emitted by electrons with power-law spectral index \( \alpha \), multiplied by the square of the photon energy, is
given by
\[ \frac{dN}{dE_\gamma} \frac{E_\gamma^2}{d\gamma} = \frac{2a_k U_k e^2}{\varepsilon_0} \left( \frac{2e^2}{\varepsilon_0} \right)^{-(a+1)/2}, \] (12)
and we use this formula for each power-law section of the electron spectrum.

The ICS part of the equation (7) cannot be obtained analytically in the general case because of the complicated form of the Klein–Nishina cross-section, and so we compute this numerically using
\[ \frac{dN}{dE_\gamma} \frac{E_\gamma^2}{d\gamma} \gamma' = E_\gamma^2 \int_{\gamma_{\text{min}}}^{\infty} \frac{dN(\gamma', E'_\gamma)}{d\gamma'} d\gamma', \] (13)
where \( \gamma'_{\text{min}} \approx E'_\gamma/mc^2 \), \( E'_{\gamma_{\text{min}}} = E'_\gamma/[4(\gamma' - E'_\gamma/mc^2)] \), \( E'_\gamma = E_\gamma/D \), and \( dN(\gamma', E'_\gamma)/d\gamma' d\gamma' \) is the ICS spectrum (see equation 2.48 in Blumenthal & Gould 1970) produced by electrons with Lorentz factor \( \gamma' \) which scatter synchrotron photons in the blob, and we use in this formula the soft photon spectrum given by equation (4).

Having obtained formulae for the synchrotron power at 2 keV (equation 12) and the inverse Compton power at 1 TeV (equation 13), we can substitute these, together with the optical depth reduction factors, into the equation for \( \eta \) (equation 7). Setting \( \eta = 3.6 \), we solve this equation numerically to obtain \( B \) as a function of \( D \) for various values of \( t_{\text{var}} \). The resulting allowed values of \( B \) versus \( D \) are plotted for \( \xi = 1 \) as the two thick full curves (for the low- and high-IRB models) in Figs 3(a)–(c) for \( t_{\text{var}} = 2.5 \) h, 20 min and 2 min respectively. Fig. 3(d) is for \( \xi = 1/3 \) and \( t_{\text{var}} = 2.5 \) h. In the next section we further constrain the allowed values of \( B \) and \( D \) by requiring the radiative time-scales to be consistent with the variability time-scale.

4 CONSTRAINTS FROM RADIATIVE TIME-SCALES

The simultaneous variability observed in TeV \( \gamma \)-rays and X-rays allow us to place a further constraint on the homogeneous SSC model. The observed decrease in the observed TeV \( \gamma \)-ray and...
X-ray fluxes may only occur if the electrons have sufficient time to cool during the flare,
\[ t_{\text{cool}}' \leq t_{\text{var}}D. \tag{14} \]

This condition is required if the model is truly homogeneous, i.e., the model we consider in the present paper which includes a homogeneous magnetic field and constant jet direction and bulk Lorentz factor. In what follows, we consider the cooling time of electrons responsible for synchrotron radiation observed at 2 keV, i.e.,
\[ \gamma' = \left( 2e/D \epsilon_0 \right)^{1/2}. \tag{15} \]
with $e = 2$ keV. The cooling time-scale for synchrotron losses of electrons with Lorentz factor $\gamma'$ is given by

$$
\tau_{\text{cool}}^{\text{syn}} = \frac{m_ec^2}{k_U \gamma'}. 
$$

We next estimate the ICS cooling time. For the soft photon spectrum we adopt, some interactions with energetic electrons will be in the Thomson regime, while others will be in the Klein-Nishina regime, i.e., with photons above $e'_T = m_ec^2/\gamma'$, and use the simple Thomson energy loss formula

$$
\tau_{\text{cool}}^{\text{ICS}} = \frac{m_ec^2}{k_U \gamma'} 
$$

where

$$
U_{\text{rad}}(< e'_T) = \int_0^{e'_T} \rho(e') e' \, de'. 
$$

Because the optical to X-ray energy flux per log energy interval, $F_{\gamma}(E) = E^2 F(E)$, increases with energy (i.e., the photon spectrum is flatter than $e^{-5}$), most of the inverse Compton energy flux will occur near $E_{\gamma} \approx D_\gamma e'_T = D_\gamma m_ec^2$.

Thus the ratio of the energy loss times for inverse Compton and synchrotron loss for electrons with energies such that they radiate synchrotron photons which are observed with energies of $e = 2$ keV is given by the ratio, $\rho$, of emitted energy flux per log energy interval observed at $e = 2$ keV to the emitted energy flux per log energy interval observed at a $\gamma$-ray energy of $E_{\gamma} = (2eD/e_B)^{1/2} m_ec^2$.

$$
\rho \approx \left( \frac{\tau_{\text{cool}}^{\text{ICS}}(\gamma')} {\tau_{\text{cool}}^{\text{syn}}(\gamma')} \right). 
$$

5 DISCUSSION AND CONCLUSIONS

We have now mapped out the allowed parameter space for $\xi = 1$ in Figs 3(a)–(c) for $t_{\text{var}} = 2.5$ h, 20 min, and 2 min respectively; Fig. 3(d) shows results for $\xi = 1/3$ and $t_{\text{var}} = 2.5$ h. Allowed combinations of $B$ and $D$ lie on the thick solid curve corresponding to the infrared absorption model assumed (the upper curve corresponds to the lower IRB model). From the constraints on the inverse Compton and synchrotron cooling time-scales, if the 2-keV X-ray flux is observed to vary during the flare with a similar time-scale as the $\gamma$-rays, then allowed combinations of $B$ and $D$ must be to the left of the thick dotted curve labelled $t_{\text{I,I}}$, and above the thick dot-dashed curve labelled $t_{\text{I,I}}$. Similarly, if the 0.2-keV X-ray flux is observed to vary during the flare with a similar time-scale as the $\gamma$-rays, then allowed combinations of $B$ and $D$ must be to the left of the thin dotted curve labelled $t_{\text{II,I}}$, and above the thin dot-dashed curve labelled $t_{\text{II,I}}$. Finally, the requirement that a $\gamma$-ray energy be less than the energy of the electron producing it constrains the allowed combinations of $B$ and $D$ to be below the thick dashed curve.

Examining Figs 3(a)–(c), we see that, as expected, as the variability time-scale decreases, the Doppler factor and magnetic field required both increase, and the allowed range of log $D$ and log $B$ decrease somewhat. Comparing Fig. 3(d) for $\xi = 1/3$ with Fig. 3(a) for $\xi = 1$, both being for $t_{\text{var}} = 2.5$ h, we see that the effect of varying $\xi$ is to increase the required magnetic field and to reduce the allowed range of log $D$.

Not all of the parts of the thick solid curves within the "allowed"
parameter space will actually give a viable SSC model, as they may predict a high-energy SED which may have a very different shape from that observed. To delineate further the allowed values of $B$ and $D$, we calculate the spectra of $\gamma$-rays emerging from the blob (after photon–photon absorption in the blob synchrotron radiation) and propagating to Earth (through the IRB). We have calculated the spectra for each of the points labelled $A$, $B$, $C$ or $D$ in Figs 3(a)–(d), and normalized these to the observed flux at 1 TeV. The results are plotted for the lower IRB model in Figs 4(a)–(d) respectively. Fig. 4(e) shows the result of using the upper IRB model (points labelled $A'$, $B'$, $C'$ and $D'$ in Fig. 3a) instead of the lower one, and we see that a worse fit to the observed spectrum results.

We now discuss which of these spectra are consistent with the observations. For the longest variability time-scale considered, $2.5\text{ h}$ (Figs 4a, d and e), the parameters corresponding to the points labelled $A$ and $B$ are ruled out because of their poor agreement with the observed spectrum, and point $C$ gives the best fit, with point D being acceptable provided that further absorption (e.g., due to photons from the accretion disc, other parts of the jet, or a dusty molecular torus; Protheroe & Biermann 1997) can steepen the spectrum. As we go to shorter variability time-scales (Figs 4b and c) only points A are ruled out by the data. Table 1 summarizes the best-fitting model parameters for each case considered.

As seen in Fig. 3(d), which is for $t_{\text{var}} = 2.5\text{ h}$ and $\xi = 1/3$, the constraint from the IC cooling time-scale and the observed variability at $0.2\text{ keV}$ is very close to ruling out the best-fitting spectrum (point $C$), and it definitely rules out the spectrum corresponding to point $D$. It has been reported by Buckley & McEnery (1999, cited by Catanese et al. 1997 and Kataoka et al. 1999) that $U$-band observations show variability simultaneous with the TeV $\gamma$-rays. Such $U$-band variability would further constrain the allowed values of $D$, as the corresponding constraint from the IC cooling time-scale would be significantly to the left of the curve labelled $t_{\text{var}}$ in Fig. 3(d), ruling out the best-fitting spectrum (point $C$). Inspection of Fig. 4(d) shows that spectra corresponding to points $A$ and $B$ in Fig. 3(d) are ruled out by their disagreement with observation. Thus the reported $U$-band observations would rule out all models with $\xi \geq 1/3$, implying that the allowed blob radius is larger than $\xi c D t_{\text{var}} / 6$.

We would like to emphasize the importance of including photon–photon absorption in calculations when determining the allowed parameters of the SSC model. For example, in previous papers the energy at which the emitted energy flux per log energy interval maximizes in the $\gamma$-ray region is used when constructing constraints, as is the ratio of the peak luminosities. However, because of photon–photon absorption the energy at which the emitted energy flux per log energy interval maximizes can be significantly higher than the energy at which the observed energy flux per log energy interval maximizes, and this can lead to an incorrect determination of the allowed parameters. For example, we show in Fig. 5 that the maximum in the $\gamma$-ray spectrum shifts to lower energies by about an order of magnitude when photon–photon absorption is included; this has consequences for the constraint obtained by Tavecchio et al. (1998) from a comparison of the location of the peaks in synchrotron and IC spectra.

Finally, we point out the importance of simultaneous multi-wavelength observations which are vital to properly determine the physical parameters of the emission region. To be most useful, these observations should cover the full energy ranges of both the low-energy (synchrotron) and high-energy (Compton) parts of the SED.

**ACKNOWLEDGMENTS**

We thank Anita Mücke for reading the manuscript and for helpful comments. WB thanks the Department of Physics and Mathematical Physics at the University of Adelaide for hospitality during his visit. This research is supported by a grant from the Australian Research Council and by the Polish Komitet Badań Naukowych grant 2P03D 001 14.

**REFERENCES**

Bednarek W., Protheroe R. J., 1997, MNras, 292, 646
Donielli L., Ghisellini G., 1995, MNras, 273, 583
Guidos J. A. et al., 1996, Nat, 383, 319

![Figure 5](https://academic.oup.com/mnras/article-abstract/310/3/577/989967/583)

**Table 1.** Parameters for the best fits to the Mrk 501 spectrum.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Spectrum</th>
<th>$t_{\text{var}}$</th>
<th>$\xi$</th>
<th>IRB model</th>
<th>$B$ (G)</th>
<th>$D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig. 3(a) C</td>
<td>Fig. 4(a)</td>
<td>2.5 h</td>
<td>1</td>
<td>lower</td>
<td>0.1</td>
<td>11.5</td>
</tr>
<tr>
<td>Fig. 3(b) B</td>
<td>Fig. 4(b)</td>
<td>20 min</td>
<td>1</td>
<td>lower</td>
<td>0.2</td>
<td>20.4</td>
</tr>
<tr>
<td>Fig. 3(c) B</td>
<td>Fig. 4(c)</td>
<td>2 min</td>
<td>1</td>
<td>lower</td>
<td>0.6</td>
<td>35.5</td>
</tr>
<tr>
<td>Fig. 3(d) C</td>
<td>Fig. 4(d)</td>
<td>2.5 h</td>
<td>1/3</td>
<td>lower</td>
<td>0.15</td>
<td>15.8</td>
</tr>
<tr>
<td>Fig. 3(a) C</td>
<td>Fig. 4(e)</td>
<td>2.5 h</td>
<td>1</td>
<td>upper</td>
<td>0.07</td>
<td>11.2</td>
</tr>
</tbody>
</table>
Punch M. et al., 1992, Nat, 358, 477

This paper has been typeset from a \LaTeX\ file prepared by the author.