In-Situ Particle Acceleration in Extragalactic Radio Hot Spots: Observations Meet Expectations

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ABSTRACT

We discuss, in terms of particle acceleration, the results from optical VLT observations of hot spots associated with radio galaxies. On the basis of observational and theoretical grounds, it is shown that: 1. relatively low radio-radio power hot spots are the optimum candidates for being detected at optical waves. This is supported by an unprecedented optical detection rate of 70% out of a sample of low radio power hot spots. 2. the shape of the synchrotron spectrum of hot spots is mainly determined by the strength of the magnetic field in the region. In particular, the break frequency, related to the age of the oldest electrons in the hot spots, is found to increase with decreasing synchrotron power and magnetic field strength. Both observational results are in agreement with an in-situ particle acceleration scenario.

Key words: Acceleration of particles - Radiation mechanisms: non-thermal - Shock waves - Galaxies: active - Galaxies: jets

1 INTRODUCTION

It is generally assumed that relativistic particles in powerful radio galaxies and quasars, initially generated in the region of the active nucleus and channeled through the radio jets out to hundreds of kpc, are re-accelerated in the radio hot spots (HSs). These regions mark the location of strong planar shocks formed at the heads of the jets by their interaction with the intergalactic medium (e.g., Begelman et al. 1984). There is evidence for electron acceleration in these regions, including their spectral energy distribution (SED), morphology and polarisation (e.g., Meisenheimer 2003, for a review). One of the most important indications in favour of electron acceleration in the HSs is still the detection of synchrotron emission at optical bands from high energy electrons (Lorentz factor $\gamma > 10^5$) with very short radiative lifetimes (e.g., Meisenheimer et al. 1997). On the other hand, it has been argued that the optical detection of radio HSs still does not make in-situ acceleration an inescapable mechanism. This is possible if one assumes a minimum loss scenario in which the relativistic electrons, injected in the nuclear region, flow in the jets losing energy only via inverse Compton (IC) scattering of Cosmic Microwave Background (CMB) photons (Gopal-Krishna et al. 2001). However, the detection of the optical emission in the southern HS of 3C 445 resolved in a complex extended structure (Prieto, Brunetti & Mack 2002) and the large-scale diffuse optical emission in Pictor A-West (Meisenheimer 2003) are difficult to be accounted for by a simple minimum loss transport scenario.

The purpose of this Letter is to test some specific predictions of the in-situ acceleration scenario with direct observations of a relatively large number of HS regions for which reliable SEDs could be determined. In brief, we discuss two predictions of the theory: 1. HSs of relatively low radio power, i.e. most likely dominated by low magnetic field values, are the optimum candidates for being detected at optical wavelengths; 2. the shape of the HS synchrotron spectra depends on the value of the magnetic field in these regions.

To that end, we have observed in the optical a sample of HSs with radio power lower by about one order of magnitude with respect to that of typical known HSs. This selection criterion, derived from simple arguments based on particle acceleration theory, led to a 70% detection rate in the optical with the VLT (Mack et al. 2003). In addition to our VLT sample, in this Letter we have compiled a data set of SEDs, from radio to optical, of a few optical synchrotron HSs from the literature and compared their properties with that of our VLT HSs.

$H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$ are used in the paper.
2 ELECTRON TRANSPORT

Relativistic electrons in powerful radio sources are produced in the nuclear regions. Under realistic assumptions for the spatial transport, the diffusion velocity of the fast particles in the jet is expected to be considerably lower than the advection velocity (e.g., Jones et al. 1999; Casse & Marcowith 2003) and thus these particles are expected to be channelled and advected into the jet up to the HSs. HSs are often located at several tens or hundreds of kpc from the nucleus of the radio galaxy and thus the travel time of the electrons up to the HS can be considerably larger than the radiative lifetime of these electrons, in particular when they are detected at optical frequencies.

One possibility is that the radiative losses of the electrons in the jet are minimized. This assumes that adiabatic and synchrotron losses in the jets are negligible with respect to the unavoidable losses due to IC scattering of the CMB photons. In the framework of this minimum loss scenario, Gopal-Krishna et al. (2001) have indeed shown that, at least in some cases, it is possible to transport high energy electrons in the jet before they have lost a substantial fraction of their energy. More specifically, if electrons in the jet are transported with a bulk velocity, \( c_\beta \), the projected maximum distance from the nucleus, \( D_{\text{max}} \), at which it is still possible to produce optical emission is:

\[
D_{\text{max}}(\text{kpc}) \simeq 43 \times \frac{\Gamma_j \beta_j \sin \psi (1+z)^{1/2}}{0.09 (1+z)^4 \beta_j^2 \Gamma_j^2 + (\frac{B_{\text{HS}}}{\mu G})^2} \times \frac{10^{15}}{100 \nu_o} \]  

where \( \Gamma_j \) is the Lorentz factor of the jet, \( B_{\text{HS}} \) and \( B_j \) are the HS and jet magnetic fields (in \( \mu G \)) respectively, \( \nu_o \) is the observed synchrotron frequency (in Hz), and \( \psi \) is the angle between jet velocity and line of sight. In Fig. 1 we show the maximum accessible distances for the electrons for different values of their bulk velocity in the jet and under a reasonable choice of values for the other parameters in Eq. 1 (see caption Fig. 1). Fig. 1 shows that the maximum possible distance, of the order of 150 kpc (for \( B_{\text{HS}} = 100 \mu G \)), is achieved for the extreme case of \( B_j = 0 \). We notice that the presence of a low magnetic field in the jet, \( B_j \sim 5 \mu G \), considerably reduces \( D_{\text{max}} \).

As a general result, Eq. 1 yields \( \nu_o \propto B_{\text{HS}}/D_{\text{max}}^2 \), i.e. the detection of high-frequency synchrotron emission is expected in HSs at small distance from the nucleus and with high magnetic field strengths.

3 PARTICLE ACCELERATION

If optical HSs are detected beyond the maximum distance achievable with a transport scenario, the high energy electrons responsible for that emission must have been accelerated in-situ, most likely via shock acceleration (e.g., Blandford & Eichler 1987). The shape of the electron spectrum accelerated in a shock region basically depends on the interplay of the acceleration efficiency with the energy losses of the electrons and with the rate of the electron diffusion from the shock region. In case of non-relativistic, diffusive shocks, the spectrum of the accelerated electrons accumulated in the HS volume is well known: a power law in momentum, \( N(p) \propto p^{-3} \), up to a break, \( p_b = m_c \gamma_b \), then a steepening up to maximum momentum, \( p_c = m_c \gamma_c \), where a cut-off is developed (e.g., Heavens & Meisenheimer 1987).

The cut-off energy is generated by the competition between acceleration and loss mechanisms in the shock region, while the break energy is the maximum energy of the oldest electron population in the HS volume and its value is driven by the cooling of the electrons in the post-shock region. Particles are accelerated in the shock region crossing back and forth between upstream and downstream flows. The scattering should be guaranteed by strong turbulence in the jet flows which can be externally produced or excited by the particles themselves (e.g., Cesarsky 1980). The efficiency of the acceleration depends on the spectrum of the turbulent waves in the flows due to the spatial diffusion coefficient of particles \( \kappa(\gamma) \) (e.g., Casse & Marcowith 2003 and ref. therein). The rate of electron energy gain is given by:

\[
\left( \frac{d\gamma}{dt} \right)_\text{sh}^+ \simeq \frac{U_-}{r} \left( \frac{r-1}{r+1} \right) \frac{1}{3 \kappa(\gamma)} \]  

where \( U_- \) is the velocity of the plasma in the downstream region and \( r \) is the compression factor. For sake of simplicity, most theoretical applications to HSs done so far assume a constant diffusion coefficient (e.g., Heavens & Meisenheimer, 1987). However, because of its dependence on the topology of the turbulent magnetic field in the shock region (e.g., Blasi 2001 and ref. therein), here, we focus on two relevant diffusion coefficients: a Kolmogorov coefficient, obtained assuming a Kolmogorov spectrum for the magnetic field in the upstream and downstream region, and a classical Bohm diffusion coefficient (e.g., Bhattacharjee & Sigl 2000, for a review):
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\[ K(\gamma) \approx \begin{cases} 
1.3 \times 10^{29} (B_{\mu G})^{-1/3} L_{\text{kpc}}^{2/3} \gamma^{1/3} & \text{Kolmogorov} \\
1.7 \times 10^{19} (B_{\mu G})^{-1} \gamma & \text{Bohm} 
\end{cases} \]  

(3)

with \( L_{\text{kpc}} \) the maximum coherence scale of the magnetic field in kpc (of the order of the HS size).

On the other hand, the rate of synchrotron and IC losses in the shock region is given by:

\[ \left( \frac{d\gamma}{dt} \right)^{\text{syn+ic}} = -S \gamma^2 \left( \frac{2}{3} B^2 + B_{\text{IC}}^2 \right) \]  

(4)

where \( S \approx 1.9 \times 10^{-9} \), and \( B \) and \( B_{\text{IC}} \) are the magnetic and IC equivalent fields (in this case in the shock region). At the zeroth order, i.e. without including non-linear effects, the maximum energy of the accelerated electrons, \( \gamma_c \), is the energy at which cooling is balanced by acceleration, i.e. (from Eqs. (2-4)):

\[ \gamma_c \sim \begin{cases} 
1.2 \times 10^5 \left( \frac{U_{\text{IC}}}{0.1c} \right)^{3/2} \left( \frac{B/(100 \mu G)}{2/3(B/(100 \mu G))^2 + (B_{\text{IC}}/(100 \mu G))^2} \right)^{3/2} \\
10^9 \sqrt{\gamma_c} \left( \frac{U_{\text{IC}}}{0.1c} \right) \left( \frac{B/(100 \mu G)}{2/3(B/(100 \mu G))^2 + (B_{\text{IC}}/(100 \mu G))^2} \right)^{3/2} 
\end{cases} \]  

(5)

in the Kolmogorov and Bohm case, respectively (\( f = (r - 1)/(r^2 + r), \ r = 4 \) for a strong shock). Eq. 5 shows that for fiducial values of the parameters electrons with \( \gamma \geq 10^9 - 10^6 \) are easily obtained, and therefore optical emission is guaranteed regardless of the distance from the core. We also notice that the corresponding cut-off frequency, \( \nu_c \propto \gamma^2_c B \), would increase with decreasing magnetic field strength (Kolmogorov case) or would be roughly constant (Bohm case).

Once the electrons are accelerated, they travel in the post-shock region filling the HS volume and cooling due to radiative losses but also due to adiabatic expansion. Without a detailed model for the HS dynamics, the break energy of the electrons can be simply parameterized as:

\[ \gamma_b(\tau) = \frac{\gamma_c}{1 + S(B^2_c)_{\gamma_c}} \times \left( \frac{u_i}{u_{HS}} \right)^{1/4} \]  

(6)

where \( \tau \) is the dynamical age of the HS, \( (B^2_c) \) gives the synchrotron and IC fields averaged over the electron time evolution, and \( (u_i/u_{HS})^{1/4} \) accounts for adiabatic losses (e.g., Manolakou & Kirk 2002; \( u_i \) and \( u_{HS} \) are the energy density in the lobe and HS, respectively) under the assumption that, at a given point, the HS expands into the lobe in a time shorter than the radiative cooling time. The corresponding synchrotron break frequency emitted in an averaged HS field, \( B_{\text{HS}} \), is thus (using Eq. 6):

\[ \nu_b = \frac{\gamma^2_c B_{\text{HS}}(u_i/u_{HS})^{1/2}}{(1 + S(B^2_c))^{3/2}} \left( \frac{u_i}{u_{HS}} \right)^{1/2} \tau^2 B_{\text{HS}}^3 \]  

(7)

for synchrotron dominated (\( B \gg B_{\text{IC}} \)) HSs. The right side of Eq. 7, (valid for \( \gamma_c \gg \gamma_b \)) is obtained for \( (B_c) \sim B_{\text{HS}} \).

Thus, Eqs. 5-7 make clear predictions on the shape of the spectrum of the shock-accelerated electrons in HSs. In particular, the weaker the magnetic field, the higher are the break and the cut-off frequencies. As a consequence, low-field HSs are the most promising candidates for being detected at optical wavelengths.

Figure 2. The spectrum of the southern HS of Cyg A (filled points and arrows - upper limits) is compared with that of the low-brightness southern HS of 3C445 (empty points). The curves are theoretical synchrotron models. The data of Cyg A South are taken from Carilli et al. (1999).

4 VLT SAMPLE AND RESULTS

4.1 Optical Detection rate

The search for optical counterparts of HSs has so far been addressed to bright radio HSs. However, only a few optical HSs were discovered in more than 20 years of observations. Because of this scarcity of detections, the exploration of low brightness HSs has never been attempted. However, as shown in Sect. 3, once the electrons are injected/accelerated in the HS volume, their radiative life-time, in low-power radio HSs (most likely with lower values of magnetic field strength), is expected to be longer than that in high-power HSs. Thus, low-power radio HSs would have higher \( \nu_c \) and emit the bulk of their radiation at high frequencies. This is sketched in Fig. 2 where a comparison between the spectrum of a high and low-power HS is given: if the general expectations derived in Sect. 3 hold, the spectra of low-power HSs are expected to remain relatively hard at high frequencies and thus, contrary to the case of the high-power ones, the optical detection rate of low-power targets is expected to be relatively high.

Thus, to test these expectations and to extend the search for optical counterparts down to relatively low-power HSs, we embarked on a project with the VLT aimed at the detection of HSs with synchrotron powers about one order of magnitude lower than those of typical optical HSs reported in the literature. Ten HS targets were selected from Tadhunter et al. (1993). Although relatively faint in the radio band, these targets turned out to be sufficiently bright in the optical to warrant a significant detection with the VLT under the assumption that their break frequencies fall in between the far-IR and optical band (assuming a synchrotron spectral index \( \alpha \sim 0.6 - 0.7; P(\nu) \propto \nu^{-\alpha} \)). Out of the 10
HSs observed with the VLT, clear detections were achieved for six of them (3C 105 South, 3C 195 South, 3C 227 West, 3C 227 East, 3C 445 North and 3C 445 South), while one of the HSs in the sample, 3C 327 East, is confused by a relatively bright spiral galaxy which hampers the detection of any HS counterpart. All together, an extremely high detection rate of 70% was achieved which basically confirms, at least qualitatively, our theoretical expectations.

4.2 Spectral Parameters and Particle Acceleration

In order to derive the spectral parameters (i.e., $\alpha = (\delta - 1)/2$, the break, $\nu_b$, and the cut-off, $\nu_c$, frequencies) of the HSs, theoretical synchrotron spectra produced by a population of accelerated electrons (following the modelling in Brunetti et al. 2002) were fit to the data (possible effects due to beaming (Georganopoulos & Kazanas 2003) are not included for simplicity). To this aim we have collected broad-band data for the HSs of our sample. In particular, VLA high-resolution images were obtained either from the NRAO-VLA archive or from new observations by us. In case of two HSs (3C 105 South and 3C 227 West) two well separated optical components, well matching the corresponding separated radio counterparts (Mack et al. 2003), were detected. Thus, the final number of VLT counterparts was equal to eight.

In the framework of the minimum-loss transport scenario, assuming a HS at a projected distance from the nucleus, $D_{HS}$, the HS magnetic field, $B^*$, required to obtain synchrotron emission up to the cut-off frequency $\nu_c$ is obtained from Eq. 1:

$$B^*(\nu_c) \simeq \left( \frac{\nu_c}{10^{15}} \right) \left( \frac{D_{HS}}{43 \text{kpc}} \right)^2 \left[ 0.09(1 + z)^{11/2} + \left( \frac{B_j}{\mu G} \right)^2 \right]^{1/2}$$

Assuming a conservative value of the jet magnetic field $B_j \sim 5 \mu G$, in Fig. 3 we report the ratio $B^*/B_{eq}$ (where $B_{eq}$ the equipartition field, computed using formulae with a low energy cut-off, e.g. Brunetti et al. 1997) calculated for all the HS components detected in our VLT sample. It can be seen that in the case of HSs with lower $B_{eq}$, extremely large fields ($B^* \sim 10^{-4} - 10^{-5} B_{eq}$) should be admitted at least in a considerable fraction of the emitting volume of the HSs to produce the observed optical emission. This is clearly because, under realistic physical conditions, the travel time from the nucleus to the HS region of the high-energy electrons emitting in the optical band is considerably longer than their cooling time. As a consequence, the results in Fig. 3 indicate the presence of in-situ particle acceleration at least for the most extreme cases.

4.3 B-field and break frequency

The high optical detection rate derived in Sect. 4.1 for low-power HSs indicates that the break frequency of these HSs is larger than that of the high-power counterparts for which only a very low detection rate has been achieved in the last years. From Eq. 7, this could be due to either the effect of stronger $B$ in powerful HSs or possible smaller emitting volumes (i.e., smaller $\tau$ in Eq. 7 for a constant velocity in the post shock region) in low-power HSs (Meisenheimer et al. 1989). We follow the simplest approach that low-power HSs have a lower magnetic field strength. Accordingly, in Fig. 4 we display the break frequency as a function of the HS magnetic field (with $B_{HS} \sim B_{eq}$). Besides the fact that we deal with only 8 detections and 3 upper limits, a relatively clear trend between $\nu_b$ and $B$ is found, suggesting that the large values of the break frequency found in the case of low-power HSs is most likely due to the effect of $B$ on the cooling of the electrons. Indeed, assuming a roughly constant emitting volume (or $\tau$ for a const. velocity in the post shock region), Fig. 4 also shows the zeroth-order approximation (no adiabatic losses) of Eq. 7 ($\nu_b \propto B^{-3/2}$, solid line). The slope of this approximation is surprisingly close to that observed.

With the aim to compare the behaviour of our VLT sample with other HSs selected to match the same range of $\nu_b$, we extracted all the flux densities of optical synchrotron HSs from the literature. In Fig. 4 we display the break frequency and the equipartition magnetic field strength derived with the same procedure described below for these 8 additional optical synchrotron HSs (Tab. 1). The radio and optical data from the literature have been combined with archive HST data when available. In this Letter we do not include the case of 3C 263E since it has been shown that the broad band spectrum of this HS might result from a combination of two different spectral components (Hardcastle et al. 2002), and the cases of 3C 196N and 3C 295N whose optical emission is best interpreted as due to synchro-self-Compton (Hardcastle 2001; Brunetti 2000). We notice that the behaviour followed by the HSs from the literature is consistent with that of the VLT ones and thus strengthen the derived $\nu_b - B_{eq}$ trend. It is clear that such a trend should be tested combining the VLT sample with a sample of HSs with relatively high values of the magnetic field and thus with an expected synchrotron break frequencies below $\sim 10^{12}$ Hz (Fig. 4).
Table 1. Optical HSs from the literature

<table>
<thead>
<tr>
<th>Name</th>
<th>z</th>
<th>log(P_{bol}) [erg/s]</th>
<th>log(\nu_b) [Hz]</th>
<th>Refs</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C 20W</td>
<td>0.174</td>
<td>42.92</td>
<td>13.0</td>
<td>[1][2]</td>
</tr>
<tr>
<td>3C 33S</td>
<td>0.0592</td>
<td>42.13</td>
<td>12.65</td>
<td>[1][2]</td>
</tr>
<tr>
<td>3C 111E</td>
<td>0.0485</td>
<td>42.04</td>
<td>13.26</td>
<td>[1][2]</td>
</tr>
<tr>
<td>3C 303W</td>
<td>0.141</td>
<td>42.4</td>
<td>13.9</td>
<td>[1][2]</td>
</tr>
<tr>
<td>3C 351L</td>
<td>0.372</td>
<td>43.5</td>
<td>12.5-13.3</td>
<td>[3][4]</td>
</tr>
<tr>
<td>3C 351J</td>
<td>0.372</td>
<td>43.4</td>
<td>12.1-12.4</td>
<td>[3][4]</td>
</tr>
<tr>
<td>3C 390.3N</td>
<td>0.056</td>
<td>41.5</td>
<td>13.2</td>
<td>[5][6]</td>
</tr>
<tr>
<td>Pic A-W</td>
<td>0.0361</td>
<td>42.36</td>
<td>14.0</td>
<td>[1][2]</td>
</tr>
</tbody>
</table>


Figure 4. The synchrotron break frequency as a function of the equipartition magnetic field for the VLT HSs (empty points), and for comparison, for optical HSs from the literature (filled points). The solid line model is $\nu_b \propto B^{-3}$ (see text). The upper limit in $B_{eq}$ is for 3C 351J for which there is some indication that the real magnetic field is lower than the equipartition one (Brunetti et al., 2001; Hardcastle et al., 2002). The large uncertainties for the $\nu_b$ of 3C 351L and 351J are caused by the errors in the HST R-band fluxes.

5 CONCLUSIONS

VLT observations of a sample of relatively low-radio power HSs has led to an unprecedented 70% detection rate of these regions in the optical. From a theoretical point of view, this result is the natural consequence of optical emitting electrons surviving longer in low power, i.e. low-$B$ field, regions than in bright and strong-field HSs.

We have shown that the combination of low magnetic fields and large distances from the core of the HSs in our VLT sample indicates the need for in-situ particle acceleration in these regions: under physically realible hypotheses, the emitting electrons are too energetic and distant from the core to be transported from the nucleus to the HS region.

We have shown that there is a trend between the magnetic field strength (equipartition) in the HS volume and the measured synchrotron break frequency for the HSs in our VLT sample. In addition, we also have shown that the behaviour of optical synchrotron HSs taken from the literature is consistent with that of our VLT HSs. This trend has the predicted shape inferred within the framework of the in-situ acceleration scenario in which the break energy of the accelerated/injected electrons is driven by the cooling in the post-shock region. The combination of our low power sample with statistical samples of high power HSs will test the reported trend: the break frequency of high power HSs is in general expected to be below $\sim 10^{12}$ Hz.

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