

The inverse-Compton ghost HDF 130 and the giant radio galaxy 6C 0905+3955: matching an analytic model for double radio source evolution

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ABSTRACT

We present new GMRT observations of HDF 130, an inverse-Compton (IC) ghost of a giant radio source that is no longer being powered by jets. We compare the properties of HDF 130 with the new and important constraint of the upper limit of the radio flux density at 240 MHz to an analytic model. We learn what values of physical parameters in the model for the dynamics and evolution of the radio luminosity and X-ray luminosity (due to IC scattering of the cosmic microwave background (CMB)) of a Fanaroff-Riley II (FR II) source are able to describe a source with features (lobe length, axial ratio, X-ray luminosity, photon index and upper limit of radio luminosity) similar to the observations. HDF 130 is found to agree with the interpretation that it is an IC ghost of a powerful double-lobed radio source, and we are observing it at least a few Myr after jet activity (which lasted 5–100 Myr) has ceased. The minimum Lorentz factor of injected particles into the lobes from the hotspot is preferred to be $\gamma \sim 10^3$ for the model to describe the observed quantities well, assuming that the magnetic energy density, electron energy density, and lobe pressure at time of injection into the lobe are linked by constant factors according to a minimum energy argument, so that the minimum Lorentz factor is constrained by the lobe pressure. We also apply the model to match the features of 6C 0905+3955, a classical double FR II galaxy thought to have a low-energy cutoff of $\gamma \sim 10^4$ in the hotspot due to a lack of hotspot inverse-Compton X-ray emission. The models suggest that the low-energy cutoff in the hotspots of 6C 0905+3955 is $\gamma \gtrsim 10^3$, just slightly above the particles required for X-ray emission.

Key words: galaxies: individual: RG J123617/HDF 130, 6C 0905+3955 – galaxies: evolution – galaxies: jets – radio continuum: galaxies – X-rays: galaxies.

1 INTRODUCTION

In this work we establish whether a consistent interpretation can be found for the currently observed properties of the double-lobed sources HDF 130 and 6C 0905+39, the former of which is thought to no longer have current jet activity. We identify at which stage in their life cycles HDF 130 and 6C 0905+3955 could be by comparing their observable features (lobe length, axial ratio, X-ray luminosity, photon index, radio flux density limit) to an analytic model for the dynamics and evolution of X-ray and radio emission of an active FR II object whose jets switch off after a time t_j developed

in Mocz et al. (2011). The models also help suggest what the physical parameters of the sources such as jet energy, jet lifetime, ambient density parameters, and injection spectrum parameters may be, some of which are difficult to determine from observation alone.

Hubble Deep Field (HDF) 130 is an extended X-ray source observed in the *Chandra Deep Field-North* X-ray image (Alexander et al. 2003). All six of the extended X-ray sources found in the 1 Ms exposure were attributed to clusters and groups by Bauer et al. (2002). However, HDF 130 has since been realised to be a double-lobed structure with extended X-ray emission due to IC scattering of the CMB (Fabian et al. 2009). While the jet is turned on in a powerful radio source, $\gamma \sim 10^4$ electrons (assuming typical magnetic field strengths) required to generate GHz synchrotron radiation in the radio band lose their energy due to radiative losses much more quickly than the $\gamma \sim 10^3$ electrons

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responsible for upscattering the CMB photons; these losses are compounded by the expansion of the plasma. Thus after jet activity ceases, the IC X-ray emission lasts longer than radio emission and the source will appear as an IC ghost of a radio lobe for some period of time. On a morphological basis, and also given the non-thermal nature of the spectrum of the extended X-ray emission from HDF 130 (Fabian et al. 2009), the extended source is most likely the lobes of a formerly powerful Fanaroff-Riley II (FR II) Fanaroff & Riley (1974) galaxy.

HDF 130 is approximately 690 kpc across as determined by Fabian et al. (2009), and such an extent is not exceptional (e.g. Mullin et al. 2008). The extended emission has a steep photon index of $\Gamma = 2.65$, which could indicate significant synchrotron cooling. HDF 130 is about half as bright at X-ray wavelengths as the giant powerful radio galaxy 6C 0905+3955 (Erlund et al. 2008), which has a spectral index of $\Gamma = 1.61$, suggesting that HDF 130 may be viewed at a later stage in its life cycle than 6C 0905+3955.

6C 0905+3955 is a powerful FR II galaxy, approximately 945 kpc in diameter (Blundell et al. 2006). The source characteristics mandate a low-energy cutoff of freshly injected particles in the hotspot above $\gamma \sim 10^3$ due to the absence of X-ray emission from the hotspot (but not the lobes) (Blundell et al. 2006; Erlund et al. 2008). The lobes, containing older plasma, do have $\gamma \sim 10^3$ particles required for observing IC scattering on the CMB in the X-ray. The higher energy particles injected from the hotspot into the lobes undergo energy loss and hence result in the presence of plentiful $\gamma \sim 10^3$ particles in the lobes. Extended IC X-ray emission has been observed in other sources as well, such as 3C 294 ($z = 1.786$) (Fabian et al. 2003), 4C 23.56 ($z = 2.48$) (Johnson et al. 2007) and 4C41.17 ($z = 3.8$) (Scharf et al. 2003). The CMB energy density is proportional to $(1+z)^4$, cancelling the dimming due to distance, and thus extended X-ray emission may be observable at both low and high redshifts (Felten & Rees 1969).

2 OBSERVATIONS OF HDF 130 AND 6C 0905+39, AND THE MODEL FOR EVOLUTION OF AN FR II OBJECT

2.1 GMRT observations of HDF 130

We observed the target HDF 130 for 9 hours on 2008 Oct 25 using the Giant Metre-wave Radio Telescope (GMRT) at 240 MHz. The observation was made in spectral line mode and had a total bandwidth of 8 MHz, consisting of 128 channels each of 62.5 kHz, for each of RR and LL polarisations, which facilitated both high-fidelity imaging across the primary beam and also efficacious excision of radio-frequency interference. Absolute amplitudes were set using observations of 3C 286. Observations of 1252+565, our chosen phase calibrator, were interleaved throughout the observation. After allowing for observations of the calibrator sources, the total on-target time was 7.3 hours giving good UV-coverage to facilitate deconvolution. These data were reduced using standard wide-field procedures within AIPS, including facetting across the full primary beam. The innermost region of the resultant image is shown in Figure 1, which has resolution of 17 arcsec by 14 arcsec. The upper limit of the radio flux density of HDF 130 at 240 MHz in an 81 arcsec by 15 arcsec area centered on the source is 11 mJy. The 3σ flux density upper limit is 33 mJy.

2.2 Previous HDF 130 observations

HDF 130 was most recently analysed in the X-ray by Fabian et al. (2009). The source is a massive ($\sim 5 \times 10^{11} M_{\odot}$ stellar population (Casey et al. 2009)) elliptical galaxy at $z = 1.99$ with a roughly double-lobed structure in the X-ray and a compact radio nucleus. Each lobe is approximately 345 kpc long with an axial ratio (single lobe length divided by width of the lobe) of 2 (Fabian et al. 2009). The X-ray image of HDF 130 observed in the *Chandra Deep Field-North* 2 Ms exposure was best modelled with a photon index of $\Gamma = 2.65$ by Fabian et al. (2009) and has a 2–10 keV luminosity of $5.4 \times 10^{43} \text{erg s}^{-1}$.

2.3 Previous 6C 0905+3955 observations

The powerful $z = 1.88$ FR II source 6C 0905+3955 was most recently observed in the X-ray by *XMM-Newton* (Erlund et al. 2008). The projected size of the source is 945 kpc (Blundell et al. 2006) with an axial ratio of 8, although the source has arm-length asymmetry (the ratio of arm lengths is 1.6) (Law-Green et al. 1995; Blundell et al. 2006). The extended X-ray lobe emission was modelled with a photon index of $\Gamma = 1.61$ and has a 2–10 keV luminosity of $1.5 \times 10^{44} \text{erg s}^{-1}$ (Erlund et al. 2008). The MERLIN 408 MHz image gives a radio luminosity of the lobes of $8.4 \times 10^{43} \text{erg s}^{-1}$ (Law-Green et al. 1995).

2.4 Model for evolution of a double radio source

We use a model for evolution of double radio sources developed in Mocz et al. (2011), where the full details may be found, in order to determine the source properties of HDF 130 and 6C 0905+3955 and their evolutionary stage at the time of observation. Here we outline some of the basic features of the model. The model is an analytic one for the dynamics and evolution of the radio luminosity and X-ray luminosity (due to IC scattering of the CMB) of FR II radio galaxies. It accounts for injection of relativistic particles into the lobes of radio galaxies, and for adiabatic, synchrotron and IC energy losses to describe the evolution of the emission in the radio and the X-ray bands assuming a powerful double-lobed radio galaxy whose jets turn off after a typical jet lifetime. The model is based on the formalisms of Kaiser et al. (1997), Kaiser & Alexander (1997), Blundell et al. (1999) and Nath (2010).

The model is characterized by the jet power Q_j (per jet), jet lifetime t_j , ambient density described by

$$\rho(r) = \rho_0 (r/a_0)^{-\beta} \quad (1)$$

and a power-law injection spectrum into the lobe of

$$n(\gamma_i, t_i) d\gamma_i = n_0 \gamma_i^{-p} d\gamma_i \quad (2)$$

with γ_i between γ_{\min} and γ_{\max} .

In the model, we have injection of relativistic electrons into the expanding lobe until jet activity stops and no further particles are added into the lobe. The energy loss equation describes the time evolution of the Lorentz factors of the electrons:

$$\frac{d\gamma}{dt} = -\gamma \frac{1}{3} \frac{1}{V_1} \frac{dV_1}{dt} - \frac{4}{3} \frac{\sigma_T}{m_e c} \gamma^2 (u_B + u_c) \quad (3)$$

where the first term is the energy loss due to the adiabatic expansion of the lobe of volume V_1 and the second term describes the synchrotron and IC losses. Here m_e is the mass of an electron, $u_c = a(2.7 \text{ K} (1+z))^4$ is the CMB photon energy density at the redshift of the source and $a = 7.565 \times 10^{-16} \text{ J K}^{-4} \text{ m}^{-3}$

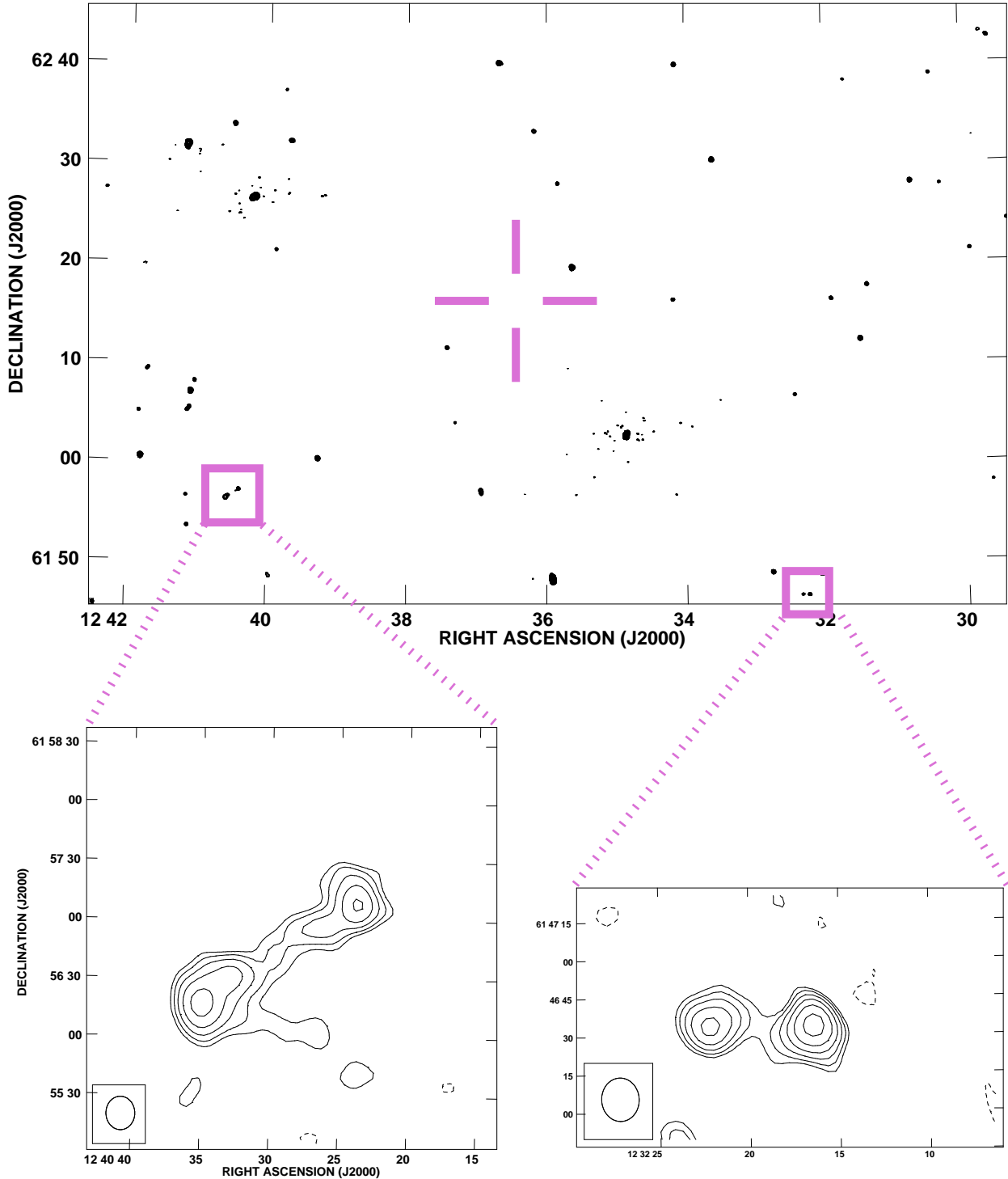


Figure 1. Wide-field image of the region of sky surrounding HDF 130, at 240 MHz, observed by the GMRT (see § 2.2). The lowest contour on the main image is 20 mJy beam^{-1} while those in the insets are 4 mJy beam^{-1} . The insets show two double radio sources far from the phase centre.

is the radiation constant. Once no more fresh particles are injected into the lobes, the X-ray photon index will steepen from what is expected from the injection spectrum index due to the synchrotron and IC energy losses.

The pressure in the lobes, the energy density of the electrons, and the energy density of the magnetic field in the model are related by constants of order unity based on minimum energy arguments,

adapted from Kaiser et al. (1997). The strength of the magnetic field is governed by the jet power (higher jet power corresponding to higher magnetic fields), and the magnetic fields do decrease in the evolution of the source as the lobes expand. The magnetic fields range between $0.1\text{--}10 \mu\text{G}$.

Typical jet energies may range from $5 \times 10^{37} \text{ W}$ to 10^{40} W , and jet lifetimes may vary from 10^6 yr to 10^9 yr . More powerful

Table 1. Model parameters tested

Parameter	values
Q_j (W)	$5 \times 10^{37}, 10^{38}, 2 \times 10^{38}, 5 \times 10^{38}, \dots, 10^{40}$
t_j (yr)	$10^5, 5 \times 10^5, 10^6, 5 \times 10^6, \dots, 10^9$
β	1.5, 2
ρ_0 (kg m^{-3})	$1.67 \times 10^{-23}, 1.67 \times 10^{-22}$
γ_{\min}	1, 10^3 , 10^4
p	2.14, 2.5, 3

jets give rise to lobes that are brighter and grow larger. During the time the jet is on, the radio luminosity decreases with time but the X-ray luminosity increases because higher energy electrons, losing their energy more quickly, downshift to Lorentz factors of $\gamma \sim 10^3$ needed for the IC scattering of CMB photons to 1 keV energies and the injection of new energetic electrons into the lobe by the jet more than compensates for the original $\gamma \sim 10^3$ electrons losing energy. Once the jet is off, there is no injection of new particles and the radio and X-ray luminosities fall (the fall is faster in the radio as higher energy electrons required for synchrotron radiation lose energy more rapidly).

One set of environmental parameters inferred from observations is: $\beta = 1.5$, $a_0 = 10$ kpc and $\rho_0 = 1.67 \times 10^{-23}$ kg m^{-3} (Blundell et al. 1999). A less dense environment would allow for sources to grow larger but luminosity then falls more quickly due to increased adiabatic losses. The injection index p is between 2 and 3 (Alexander & Leahy 1987). The maximum injected Lorentz factor γ_{\max} is set to 10^6 as Lorentz factors of $\gamma \sim 10^3$ are required to produce upscattering of the CMB in the X-ray and Lorentz factors of $\gamma \geq 10^4$ are needed for GHz synchrotron radiation in the radio for typical magnetic field strengths of $B \sim 0.1\text{--}10$ μG . The minimum injected Lorentz factor γ_{\min} may in principle be as low as 1.

The output luminosities of the model are in units of power per frequency per steradian, which is converted to a power (units of erg s^{-1}) by multiplying by 4π steradians and the frequency ν of the emission.

3 RESULTS

Our physical model for the radio source has 8 parameters (jet energy, jet lifetime, minimum injected Lorentz factor γ_{\min} , injection power spectrum index p , β and ρ_0 characterizing the environment, and the time of observation). We have five predicted observables (lobe length, axial ratio, X-ray luminosity, photon index, radio flux density limit). Therefore we cannot fit the model to the 5 data points since we would be overfitting. However, we can do something simple. We can consider a wide range of parameters which observations suggest describe most double-lobed radio sources and test which combinations of parameters can yield an object that is similar to HDF 130 or 6C 0905+3955. Looking at the sets of parameters that do well will indicate what types of scenarios may be possible. We are not able to conclude the value of any physical parameter specifically but can learn that certain values for a specific parameter in the model may be unable to reproduce observed source properties. The length of time of the observational window during which a specific set of physical parameters leads to a model similar to the observed source gives an estimate of the likelihood of the model. Without considering the observational window, all the sets of parameters that describe a source similar to the observed properties

are equally likely candidates to describe the source. But considering the observational window, a model that describes a source with similar features to the observed source for only a very brief period of time is less probable to be the correct descriptor than a model that does so for a longer window. In order to estimate whether one value, x_1 for a parameter x may be preferred over another, x_2 , in a Bayesian sense, one may compare the total length of time of the congruent observational windows of all the models investigated with $x = x_1$ to all the models with $x = x_2$.

The source parameters being fit are obtained from the observations mentioned in § 2. We list the parameters here: HDF 130 has lobe of length 345 kpc, axial ratio 2.0, 1 keV X-ray luminosity of 8.5×10^{43} erg s^{-1} , $\Gamma = 2.65$ and upper limit of the radio luminosity at 240 MHz of 2.3×10^{42} erg s^{-1} . 6C 0905+3955 has lobe of length 472 kpc, axial ratio 8.0, 1 keV X-ray luminosity of 22.3×10^{43} erg s^{-1} , $\Gamma = 1.61$ and radio luminosity at 408 MHz of 83.5×10^{42} erg s^{-1} .

We consider a range of parameters and test which models (at some point in their evolution, the congruent observational window, denoted by t_{obs}) give a lobe length, axial ratio, X-ray luminosity and photon index that agree with HDF 130 to within 30 per cent as well as a 240 MHz radio luminosity that is below the 3σ flux density limit (this percentage is arbitrary but was chosen to be large to search for sets of parameters that model sources similar to the observations without having to narrow down any parameter too precisely). We also test which models agree with 6C 0905+3955 to within 60 per cent (a higher margin of error is considered for this source as it is asymmetric which our model does not account for). We look at jet energies ranging from 5×10^{37} W to 10^{40} W, jet lifetimes from 10^5 years to 10^9 years, $\beta = 1.5$ and 2, $\rho_0 = 1.67 \times 10^{-23}$, 1.67×10^{-22} kg m^{-3} , γ_{\min} of 1, 10^3 and 10^4 , and injection indices of 2.14, 2.5 and 3. The parameters considered are listed in Table 1. A total of 2304 models were tested by considering all combinations of the parameters in Table 1. Of these 2304 runs, 19 end up closely resembling all five of the observational features of HDF 130 at some point in the evolution of the source. These models are presented in Table 2. The models that closely describe 6C 0905+3955 are presented in Table 3. The predicted observable features of the congruent models are presented in Tables A1 and A2 of the Appendix, and are compared to the observed values. Figure 2 shows an example (model [14] for HDF 130) of how X-ray luminosities and radio luminosities are predicted by the model to evolve with time.

We may obtain a constraint on p from Γ for an active source. The value of p is probably steeper than the value implied by Γ (namely, $p = 2\Gamma - 1$) to reflect the empirical point that for an active classical double radio source the spectrum has a gradient flatter at lower γ (which may reflect a cutoff/turnover/ γ_{\min}) and not representative of the high γ particles responsible for GHz emission. Table 3 for the source 6C 0905+3955 shows the values of p greater than the value implied by Γ in bold. For a source that has turned off, such as HDF 130, the observed Γ grows with time regardless of the value of p for the injection spectrum, so we cannot make such a constraint.

The models that do reasonably well at describing a source similar to HDF 130 all suggest that the source is being viewed after the jets have turned off (by at least 5 Myr) while the radio lobe emission is falling rapidly or has already dropped to below telescope sensitivity. All models except one (which has a short observational window) require γ_{\min} to be 1000 rather than 1. With $\gamma_{\min} = 1$ the FR II object in the models are not bright enough in the X-rays (see § 3.1 for a discussion on the effects of varying γ_{\min}) during the

Table 2. Models that agree with HDF 130 observations

#	Q_j^a	t_j^b	γ_{\min}	p	β	ρ_0^c	t_{obs}^d
[1]	1	100	1000	3	1.5	16.7	1.07 to 1.11
[2]	2	100	1000	3	2	16.7	1.05 to 1.11
[3]	5	50	1000	2.5	1.5	1.67	1.13 to 1.29
[4]	5	50	1000	2.5	1.5	16.7	1.16 to 1.27
[5]	5	50	1000	3	1.5	1.67	1.11 to 1.31
[6]	5	50	1000	3	2	16.7	1.18 to 1.27
[7]	5	100	1000	2.14	1.5	16.7	1.09 to 1.11
[8]	5	100	1000	2.5	1.5	16.7	1.10 to 1.15
[9]	10	50	1000	2.14	1.5	16.7	1.16 to 1.20
[10]	10	50	1000	2.14	2	16.7	1.17 to 1.31
[11]	10	50	1000	2.5	1.5	16.7	1.16 to 1.20
[12]	10	50	1000	2.5	2	16.7	1.25 to 1.33
[13]	10	100	1000	2.14	1.5	16.7	1.10 to 1.13
[14]	20	10	1000	2.5	2	1.67	1.70 to 1.95
[15]	20	10	1000	3	2	1.67	1.68 to 2.04
[16]	20	50	1000	2.14	1.5	16.7	1.18 to 1.22
[17]	50	50	1	2.14	1.5	16.7	1.15 to 1.18
[18]	100	5	1000	2.14	2	1.67	2.45 to 2.53
[19]	100	5	1000	2.5	2	1.67	2.45 to 2.49

^a ($\times 10^{38}$ W) ^b (Myr) ^c ($\times 10^{-23}$ kg m $^{-3}$)
^d ($\times t_j$)

Table 3. Models that agree with 6C 0905+3955 observations

#	Q_j^a	γ_{\min}	p	β	ρ_0^b	t_{obs}^c
[1]	50	1	2.14	1.5	1.67	0.42 to 0.52
[2]	50	1	2.14	2	1.67	0.54 to 0.60
[3]	50	1000	2.14	1.5	1.67	0.45 to 0.52
[4]	50	1000	2.14	2	1.67	0.21 to 0.28
[5]	50	1000	2.5	2	1.67	0.17 to 0.28
[6]	50	1000	3	2	1.67	0.17 to 0.28
[7]	100	1	2.14	1.5	1.67	0.30 to 0.41
[8]	100	1	2.14	2	1.67	0.21 to 0.22
[9]	100	1	2.14	2	16.7	0.42 to 0.47
[10]	100	1000	2.14	2	1.67	0.21 to 0.22

^a ($\times 10^{38}$ W) ^b ($\times 10^{-23}$ kg m $^{-3}$) ^c ($\times 100$ Myr)

times when the other parameters (length, photon index, etc.) agree within ± 30 per cent error to what is observed for HDF 130. The models suggest that the jet lifetime of HDF 130 is on the order of 1–100 Myr, and that the source was powerful, with jet power on the order of 10^{38} – 10^{40} W. The window in the time evolution of the source during which it is consistent with HDF 130 in the different models is typically a few Myr.

The models imply a long jet lifetime of at least 20 Myr for 6C 0905+3955, but we can only place a lower limit for jet lifetime for an active jet. The jet power is strong: 5×10^{39} – 10^{40} W. A γ_{\min} of 1000 (or, briefly, 1) are preferred over $\gamma_{\min} = 10^4$ to accurately describe the lobe luminosity in both the X-ray and radio simultaneously. Likely γ_{\min} is similar to or somewhat higher than 1000, as no X-ray emission (other than the synchrotron extrapolation observed by Erlund et al. (2008) with XMM) is observed in the hotspots of the source. The models under-predict the unusually

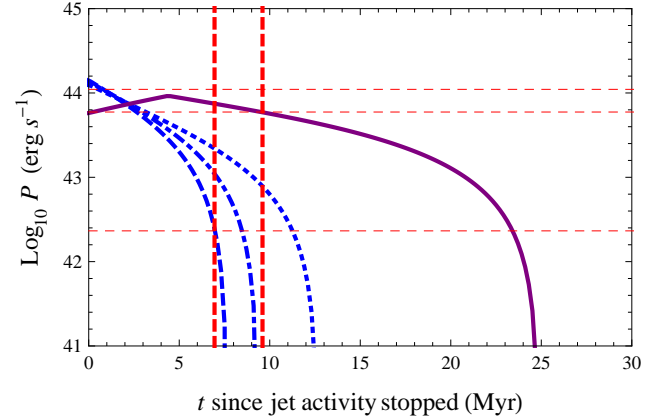


Figure 2. Evolution of X-ray and radio luminosities of model [14] for HDF 130 after jet activity has halted. The solid track shows the 1 keV X-ray power. The dashed/dot-dashed/dotted blue lines show the evolution of the 240/151/74 MHz luminosities. Vertical dashed lines show the duration in the evolution of the source that is similar to HDF 130. The horizontal thin dashed lines show the ± 30 per cent range of acceptable X-ray luminosities and the 3σ 240 MHz luminosity upper limit of emission.

large axial ratio of 6C 0905+3955 and this may be due to the fact that we averaged the two asymmetric arm lengths.

3.1 The effects of γ_{\min}

The question arises why changing γ_{\min} has an effect on the evolution of the source because the electrons below γ_{\min} do not contribute to the 1keV X-ray and 151MHz radio emission. In short, increasing γ_{\min} only from a set of given parameters will drive the source to become brighter without changing lobe growth because the electron energy density of the injection spectrum in our model stays the same as it is assumed to be linked, by a minimum energy argument, to the lobe pressure by a constant factor, and the pressure is determined by the jet power and the environmental parameters. Having the injected electron energy density kept constant but increasing γ_{\min} yields more higher γ particles (see the two solid color injection spectra in Figure 3) and hence a brighter source at 1keV and 151MHz. Alternatively, we can ask ourselves what is the effect of extending the electron energy spectrum below γ_{\min} , without keeping electron energy density constant. If we assume an injected electron spectrum with high γ_{\min} and then extrapolate the spectrum to include lower γ particles (see the dashed injection spectrum in Figure 3) then this will increase the energy density of electrons, hence the pressure and the dynamics of the source are altered and the lobes grow much larger. The combination of lobe size and source brightness will constrain possible values of γ_{\min} in our sources.

4 DISCUSSION AND CONCLUSION

We matched the observational features of HDF 130 and 6C 0905+3955 to analytic models of the evolution of the lobe length, axial ratio, photon index, and X-ray and radio luminosities of an FR II object. *Only periods of time when the source is no longer active in the models are congruent to the observations of HDF 130, supporting the idea that HDF 130 is an IC ghost of a giant radio source.* The models suggest HDF 130 experienced jet activity for a period of around 5–100 Myr, and that we are viewing

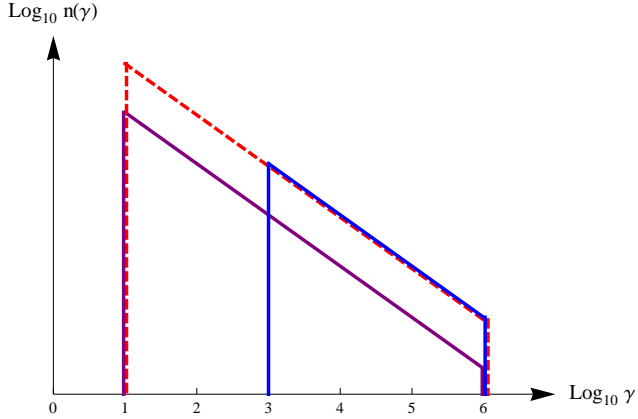


Figure 3. The effect of γ_{\min} on the injection spectrum. Increasing the parameter γ_{\min} alone while conserving the electron energy density in our model (which is linked to the pressure at time of injection into the lobe) results in more higher γ particles (see the two solid color injection spectra), making the source brighter. This is because the electron energy density is determined by a minimum energy argument and is linked to the lobe pressure, which is determined from the jet power and the environmental parameters. Extending a spectrum to include lower γ particles (dashed spectrum), which may seem innocuous because these particles do not contribute to the 1keV X-ray and 151MHz radio emission, increases the energy density of electrons, hence the pressure, and alters the growth of the lobes.

the object at least a few Myr after the jets have turned off, which is why the source is not bright in the radio. 6C 0905+3955 is inferred to have had an active jet for at least 20 Myr and may have a slightly higher intrinsic jet power than HDF 130.

Predicted radio luminosities at lower frequencies (151 and 74 MHz) for the models that agree with HDF 130 are included in Table A1. Even at 151 MHz the ghost source may not be observable. However, the models predict that the source will be observable in the 74 MHz band, with luminosity on the order of 10^{43} erg s $^{-1}$, or, equivalently, 10^{20} W Hz $^{-1}$ sr $^{-1}$. New low-frequency observations of HDF 130 could test this.

Some models predict the lobe lengths in the lower limit of the error tolerance during the observational congruent window of HDF 130, while predicting the other features accurately. If such is the case, perhaps the surrounding density profile is not as simple as we have assumed it to be and allows for the lobes to grow larger than in our models while staying bright in the X-ray. It is plausible that the source is expanding into a pre-existing lobe from a previous episode of jet activity, which cleared away some of the surrounding material and would mean expansion losses are smaller and the lobes can grow larger and brighter.

Importantly, the minimum Lorentz factor of injected particles into the lobe for HDF 130 is found to be on the order of $\gamma_{\min} = 1000$ rather than $\gamma_{\min} = 1$. Even a $\gamma_{\min} = 30$ or $\gamma_{\min} = 100$ is not preferred by HDF 130: repeating fitting the observable properties of HDF 130 with models that have $\gamma_{\min} = 30$ and $\gamma_{\min} = 100$ gives only 4 congruent models observational windows of at most 3 Myr, reported in Table 4.

In the model, a higher γ_{\min} (while keeping injected electron energy density constant) will produce brighter sources without affecting the lobe growth, which is determined by the jet power and the surrounding density profile. Increasing the jet power makes the jet grow larger and brighter. It is the combination of HDF 130 lobe size, which is not exceptionally large, and X-ray brightness which

Table 4. Additional models investigated that agree with HDF 130 observations

#	Q_j^a	t_j^b	γ_{\min}	p	β	ρ_0^c	$t_{\text{obs}} (\times t_j)$
[1]	50	50	30	2.14	1.5	16.7	1.16 to 1.21
[2]	10	100	100	2.14	1.5	16.7	1.09 to 1.12
[3]	20	50	100	2.14	1.5	16.7	1.16 to 1.20
[4]	50	50	100	2.5	1.5	16.7	1.15 to 1.18

^a ($\times 10^{38}$ W) ^b (Myr) ^c ($\times 10^{-23}$ kg m $^{-3}$)

forces the model to require $\gamma_{\min} \sim 1000$ to agree with the observational features.

The minimum injected Lorentz factor for 6C 0905+3955 is also found to be most likely on the order of $\gamma_{\min} = 1000$ (or also marginally 1), based on only best matching the total lobe luminosities predicted by the model to the observed luminosities. Considering only the models where p is steeper than implied by Γ (these values are bold in Table 3), we see that only $\gamma_{\min} = 1000$ is preferred. In previous observations, no X-ray emission is seen in a hotspot of 6C 0905+3955 (other than highly energetic X-ray synchrotron requiring extremely high Lorentz factors Erlund et al. (2008)) which suggests that there is a low-energy cutoff of the freshly injected particles into the lobe above the $\gamma \sim 10^3$ particles required for X-ray emission from upscattering on the CMB. Likely, the minimum energy cutoff is just above the critical Lorentz factor which would result in X-ray emission from the hotspot. It is important to note that 6C 0905+3955 may be more complicated than described by our simple model, because 6C 0905+3955 is asymmetric, probably due to an asymmetric surrounding environment. There may also be complex mechanisms happening in the lobes, such as reflected shocks or interruptions of the jet at the hotspot (Law-Green et al. 1995), which are so far unaccounted for by our model.

The chosen value of γ_{\min} varies by orders of magnitude in previous papers, as it often has to be estimated. The minimum Lorentz factor is assumed to be typically 1 in previous models of FR II evolution by Kaiser et al. (1997), Kaiser & Alexander (1997), Blundell et al. (1999) and Nath (2010). Croston et al. (2005) use a value of 10, Carilli et al. (1991) use a value of 100, and Wardle et al. (1998) use a value of 1000. If HDF 130 and 6C 0905+3955 are typical sources, it may be the case that the minimum energy of particles injected into the lobes is large. The value of γ_{\min} may at first appear as an eclectic, unimportant detail, but Mocz et al. (2011) show that the typical value of γ_{\min} can significantly affect estimates for the total population of FR II sources from a radio luminosity function as it changes the time sources fall below a given flux limit in their evolution. A higher γ_{\min} will also increase the detectability of IC ghosts.

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APPENDIX A: MODEL PREDICTIONS

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Table A1. Model predictions during congruent observational window compared to HDF 130 observations

#	lobe length ^a	axial ratio	$L_{x,1\text{keV}}$ ^b	Γ	$L_{r,240\text{MHz}}$ ^c	$L_{r,151\text{MHz}}$ ^d	$L_{r,74\text{MHz}}$ ^e
obs.	345	2.0	8.5	2.65	< 2.3		
[1]	278 to 281 (-0.2 to -0.19) ^f	2.1 to 2.1 (0.05 to 0.05)	7.8 to 6.2 (-0.08 to -0.27)	2.6 to 3.1 (-0.03 to 0.18)	1.3 to 0 (1.62 to 0) ^g	3.8 to 0.1	10.5 to 3.5
[2]	435 to 444 (0.26 to 0.29)	2.5 to 2.5 (0.25 to 0.25)	6.2 to 6.1 (-0.27 to -0.28)	2.0 to 2.9 (-0.25 to 0.09)	0.5 to 0 (0.63 to 0)	1.0 to 0	2.3 to 0.3
[3]	391 to 408 (0.13 to 0.18)	2.6 to 2.6 (0.3 to 0.3)	7.8 to 6.0 (-0.08 to -0.29)	1.9 to 2.7 (-0.27 to 0.03)	1.8 to 0 (2.32 to 0)	3.8 to 0	7.1 to 0.1
[4]	306 to 317 (-0.11 to -0.08)	2.4 to 2.4 (0.18 to 0.18)	8.7 to 5.9 (0.03 to -0.3)	2.3 to 2.8 (-0.12 to 0.07)	1.5 to 0 (1.89 to 0)	5.8 to 0	13.3 to 2.0
[5]	389 to 410 (0.13 to 0.19)	2.6 to 2.6 (0.3 to 0.3)	10.7 to 6.5 (0.26 to -0.23)	2.0 to 3.4 (-0.24 to 0.29)	1.7 to 0 (2.25 to 0)	3.7 to 0	8.0 to 0
[6]	308 to 317 (-0.11 to -0.08)	2.4 to 2.4 (0.18 to 0.18)	10.9 to 6.8 (0.28 to -0.2)	2.8 to 3.4 (0.07 to 0.29)	0 to 0 (0.01 to 0)	1.6 to 0	9.0 to 0.9
[7]	363 to 365 (0.05 to 0.06)	2.3 to 2.3 (0.16 to 0.16)	6.8 to 6.1 (-0.2 to -0.28)	2.2 to 2.4 (-0.15 to -0.11)	1.0 to 0 (1.3 to 0)	6.8 to 1.6	14.2 to 10.0
[8]	364 to 369 (0.05 to 0.07)	2.3 to 2.3 (0.16 to 0.16)	10.3 to 6.9 (0.21 to -0.19)	2.6 to 3.3 (-0.01 to 0.23)	0 to 0 (0 to 0)	2.9 to 0	13.9 to 1.7
[9]	249 to 252 (-0.28 to -0.27)	2.2 to 2.2 (0.09 to 0.09)	7.3 to 6.1 (-0.13 to -0.28)	2.4 to 2.8 (-0.09 to 0.04)	0.4 to 0 (0.56 to 0)	24.4 to 0.7	54.2 to 34.6
[10]	387 to 404 (0.12 to 0.17)	2.6 to 2.6 (0.29 to 0.29)	8.6 to 6.0 (0.01 to -0.29)	2.1 to 2.7 (-0.22 to 0)	2.0 to 0 (2.6 to 0)	9.0 to 0	16.9 to 0.3
[11]	249 to 252 (-0.28 to -0.27)	2.2 to 2.2 (0.09 to 0.09)	10.9 to 8.3 (0.28 to -0.02)	2.8 to 3.3 (0.07 to 0.26)	0 to 0 (0 to 0)	19.3 to 0	68.2 to 36.7
[12]	397 to 406 (0.15 to 0.18)	2.6 to 2.6 (0.29 to 0.29)	10.8 to 7.6 (0.27 to -0.1)	2.7 to 3.4 (0.02 to 0.28)	0 to 0 (0 to 0)	0 to 0	5.8 to 0
[13]	444 to 447 (0.29 to 0.3)	2.5 to 2.5 (0.25 to 0.25)	10.8 to 9.1 (0.27 to 0.07)	2.3 to 2.6 (-0.13 to -0.03)	0 to 0 (0 to 0)	7.6 to 0	22.4 to 11.2
[14]	243 to 257 (-0.3 to -0.26)	2.5 to 2.5 (0.25 to 0.25)	7.4 to 6.0 (-0.12 to -0.3)	2.1 to 2.4 (-0.19 to -0.11)	2.2 to 0 (2.84 to 0)	10.7 to 0	21.6 to 8.2
[15]	242 to 262 (-0.3 to -0.24)	2.5 to 2.5 (0.25 to 0.25)	9.9 to 6.0 (0.16 to -0.3)	2.6 to 3.1 (-0.03 to 0.17)	0.9 to 0 (1.19 to 0)	6.6 to 0	20.1 to 2.4
[16]	305 to 309 (-0.12 to -0.11)	2.3 to 2.3 (0.17 to 0.17)	10.7 to 8.5 (0.26 to 0)	2.7 to 3.3 (0 to 0.23)	0 to 0 (0 to 0)	16.1 to 0	76.6 to 41.9
[17]	393 to 397 (0.14 to 0.15)	2.6 to 2.6 (0.3 to 0.3)	7.3 to 6.2 (-0.14 to -0.27)	2.5 to 2.8 (-0.05 to 0.07)	0.5 to 0 (0.68 to 0)	31.6 to 6.2	70.4 to 50.1
[18]	242 to 245 (-0.3 to -0.29)	2.6 to 2.6 (0.29 to 0.29)	6.3 to 6.0 (-0.26 to -0.3)	2.5 to 2.7 (-0.04 to 0.02)	0 to 0 (0 to 0)	0 to 0	31.9 to 23.9
[19]	242 to 243 (-0.3 to -0.29)	2.6 to 2.6 (0.29 to 0.29)	7.7 to 7.4 (-0.09 to -0.13)	3.3 to 3.4 (0.25 to 0.29)	0 to 0 (0 to 0)	0 to 0	25.6 to 20.9

^a (kpc)^b ($\times 10^{43}$ erg s⁻¹)^c ($\times 10^{42}$ erg s⁻¹)^d ($\times 10^{42}$ erg s⁻¹)^e ($\times 10^{42}$ erg s⁻¹)^f fractional deviation^g fraction of 1 σ upper limit

Table A2. Model predictions during congruent observational window compared to 6C 0905+3955 observations

#	lobe length ^a	axial ratio	$L_{x,1\text{keV}}$ ^b	Γ	$L_{r,408\text{MHz}}$ ^c
obs.	472	8.0	22.3	1.61	83.5
[1]	626 to 752 (0.33 to 0.59)	3.2 to 3.3 (-0.6 to -0.58)	10.2 to 11.2 (-0.54 to -0.5)	1.8 to 1.8 (0.1 to 0.11)	46.5 to 34.0 (-0.45 to -0.6)
[2]	675 to 750 (0.43 to 0.59)	3.2 to 3.3 (-0.6 to -0.59)	11.6 to 12.0 (-0.48 to -0.46)	1.8 to 1.8 (0.12 to 0.13)	50.1 to 41.0 (-0.4 to -0.51)
[3]	664 to 752 (0.41 to 0.59)	3.2 to 3.3 (-0.59 to -0.58)	19.8 to 21.3 (-0.11 to -0.04)	1.0 to 1.1 (-0.35 to -0.32)	131.1 to 105.7 (0.56 to 0.26)
[4]	566 to 754 (0.2 to 0.6)	3.4 to 3.6 (-0.58 to -0.55)	9.0 to 10.7 (-0.6 to -0.52)	0.8 to 0.8 (-0.53 to -0.48)	77.9 to 46.0 (-0.07 to -0.45)
[5]	458 to 754 (-0.03 to 0.6)	3.2 to 3.6 (-0.6 to -0.55)	14.2 to 19.0 (-0.36 to -0.15)	0.7 to 0.9 (-0.54 to -0.46)	131.0 to 49.8 (0.56 to -0.41)
[6]	458 to 754 (-0.03 to 0.6)	3.2 to 3.6 (-0.6 to -0.55)	21.0 to 27.7 (-0.06 to 0.24)	0.8 to 0.9 (-0.52 to -0.44)	112.8 to 37.5 (0.34 to -0.55)
[7]	572 to 748 (0.21 to 0.58)	3.2 to 3.4 (-0.6 to -0.57)	14.6 to 17.2 (-0.34 to -0.23)	1.7 to 1.8 (0.08 to 0.1)	132.4 to 89.4 (0.58 to 0.06)
[8]	713 to 747 (0.51 to 0.58)	3.7 to 3.7 (-0.54 to -0.53)	9. to 9.2 (-0.6 to -0.59)	1.6 to 1.6 (0.02 to 0.02)	42.2 to 38.9 (-0.5 to -0.54)
[9]	662 to 741 (0.4 to 0.57)	3.3 to 3.4 (-0.59 to -0.58)	17.4 to 18.4 (-0.22 to -0.18)	1.8 to 1.8 (0.11 to 0.12)	130.7 to 108.2 (0.56 to 0.29)
[10]	713 to 747 (0.51 to 0.58)	3.7 to 3.7 (-0.54 to -0.53)	15.1 to 15.5 (-0.32 to -0.3)	0.8 to 0.8 (-0.53 to -0.52)	131.1 to 121. (0.56 to 0.44)

^a (kpc)^b ($\times 10^{43}$ erg s⁻¹)^c ($\times 10^{42}$ erg s⁻¹)