Jets from Radio Pulsars

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Abstract

The observational evidence for jets and phenomena arising from rotation powered radio pulsars is reviewed, including many recent and exciting discoveries at X-ray wavelengths. The well studied jets of the Crab pulsar are summarised, including recent results from the HST. The evolutionary links between the known binary radio pulsars and jets sources in X-ray binaries are discussed.

1 Introduction

In 1986, Feigelson [16] reviewed the evidence for jets from neutron stars and concluded that "single neutron stars do not make jets but neutron stars in binary systems can", with the speculative corollary that "the presence of accretion disks" is responsible for jets in binary neutron stars. Ten years of further study, new instruments and ideas have resulted in the discovery of several Galactic systems with jets or candidates for jets, some of which are associated with single neutron stars. Accretion powered X-ray binaries are discussed in considerable detail by Fender and others in these proceedings. In this paper the observational evidence for jets from rotation powered radio pulsars is reviewed and is summarised in Table 1. The sample of radio pulsars which have jets or candidate jets is described in §2 while the Crab, being the best example is discussed separately in more detail in §3. The evolutionary relationships between binary radio pulsars and Galactic jet sources are highlighted in §4.

The term "jet" has been applied to detections (at any wavelength) of elongated emission regions which may be due to a collimated flows of particles or material. Although a more rigorous definition, requiring the detection of proper motion of the jet is desirable there are numerous objects for which the detection of proper motion is improbable, if not impossible because of instrumental limitations. For example, it is unlikely that proper motions of X-ray jets will be measured in the near future.
Table 1
Radio pulsars with jets and related objects. †See §3

| Pulsar         | Observational Evidence                                                                 | Ref.   |
|---------------|----------------------------------------------------------------------------------------|--------|
| B0355+54      | X-ray jet, non-thermal (Einstein)                                                       | [27]   |
| J0437−4715    | Ha bow shock, ram pressure balance                                                      | [8]    |
|               | X-ray nebula (ASCA)                                                                     | [38]   |
| B0531+21†     | Double X-ray jet + torus (ROSAT)                                                        | [3,29] |
|               | Single optical jet, line free continuum                                                 | [29]   |
|               | Perpendicular expansion of counter jet channel                                          | [29]   |
|               | Single optical jet, III aJ, OIII, Ha, NII                                              | [56,59,25] |
|               | Perpendicular expansion 260 km s⁻¹                                                     | [45,51]|
|               | Linear expansion of 2500 km s⁻¹                                                        | [18,17]|
|               | Radio jet coincident with optical jet                                                   | [57,20]|
|               | B field + jet aligned, non-thermal                                                     | [58,5] |
| B0540−69      | Ha jet and NII ring (HST)                                                               | [12]   |
| J0633+1746    | X-ray filamentary extended emission (ASCA)                                              | [38]   |
| B0656+14      | X-ray jet (ASCA)                                                                        | [39]   |
| B0833−45      | Wisps interpreted as jet termination shock                                              | [10]   |
|               | X-ray jet, non-thermal (ASCA)                                                           | [38]   |
|               | X-ray jet (ROSAT, Einstein)                                                             | [46,26]|
|               | X-ray bullets (ROSAT)                                                                  | [4,53] |
| B1046−58      | X-ray nebula (ASCA)                                                                     | [39]   |
| B1055−52      | X-ray jet, non-thermal (Einstein)                                                       | [27,38]|
| B1259−63      | Radio continuum jet inferred - not resolved                                            | [30]   |
|               | X-rays from interacting winds (ASCA)                                                    | [35]   |
| B1509−58      | X-ray jet, non-thermal + thermal nebula (ASCA)                                          | [54]   |
|               | X-ray nebula (Einstein)                                                                 | [50]   |
|               | X-ray jet (ROSAT)                                                                      | [24]   |
| B1610−50      | X-ray nebula, thermal (ASCA)                                                            | [39]   |
|               | SNR with radio jet                                                                      | [48]   |
| B1718−19      | Eclipsing pulsar, illuminated companion                                                 | [42]   |
| B1744−24A     | Eclipsing pulsar, illuminated companion                                                 | [44]   |
| B1757−24      | Pulsar out running SNR                                                                  | [21]   |
| B1853+01      | Radio bow shock, ram pressure balance                                                   | [19]   |
| B1929+10      | X-ray bow shock (ROSAT)                                                                 | [60]   |
|               | X-ray nebula, non-thermal (ASCA)                                                        | [39]   |
| B1951+32      | Ha bow shock, ram pressure balance                                                      | [28]   |
|               | X-ray nebula (ASCA)                                                                     | [39,49]|
| B1957+20      | X-ray nebula (ROSAT)                                                                    | [23]   |
|               | Ha bow shock, ram pressure balance                                                      | [40,1] |
|               | Eclipsing pulsar, illuminated companion                                                 | [2]    |
| J2051−0827    | Eclipsing pulsar, illuminated companion                                                 | [52]   |
| B2224+65      | Ha bow shock, ram pressure balance                                                      | [15]   |
There are a number of objects associated with pulsars which result from the emission of relativistic particles which are not collimated. These are briefly mentioned in this paragraph, with references to recent reviews. Pulsar wind nebulae result from bow shocks where pulsar winds are balanced by ram pressure in the interstellar medium (ISM) [14]. While these objects are detected in Hα and are rare, they may be used to determine pulsar distances, radial velocities, ISM neutral hydrogen content and the soft X-ray composition of the pulsar winds. Recently many have been observed in X-rays using ASCA [38]. There are presently four eclipsing pulsars known and all of these are millisecond pulsars [22]. A significant fraction of the pulsars’ flux at all wavelengths impinges on the companion and heats it. For two of the four systems this is clearly observed as an optical brightening of the companion at superior conjunction, and offers constraints on the composition of the pulsar wind. Finally, there is the case of bullets around the Vela supernova remnant [4,53]. These are detected in both X-rays and radio and appear to be lumps of material ejected at the time of the supernova explosion.

2 Pulsars with Jets

There are a number of pulsars which may be responsible for jets, though none of these jets are known to be relativistic. A quick inspection of Table 1 reveals that at present the X-ray band offers the most prospects, with claims of X-ray jets for at least 6 pulsars. In some cases (PSRs B0355+54, B1055−52, B1929+10) these linear X-ray sources can be interpreted as mini-Crab nebulae, resulting from non-collimated relativistic particles confined by ram pressure as the pulsar moves through the ISM, leaving a wake of X-ray emission [16,27,60].

There are several cases in which this interpretation does not fit with the observations and the case for collimated emission is stronger. For the Vela pulsar (B0833−45) the X-ray jet discovered using the Einstein observatory [26] does not line up with the pulsar proper motion [7,12]. Using a ROSAT image Markwardt and Ögelman [46] incorrectly interpreted the jet as thermal, while recent ASCA observations clearly revealed a non-thermal spectrum [38]. There are strongly polarised linear features in the radio maps of Milne [47] that may be associated with the X-ray jet, though these have not been interpreted as a radio jet. Tamura et al. [54] recently used ASCA observations of PSR B1509−52 to demonstrate that it has both a non-thermal X-ray jet generated by the pulsar and a thermal X-ray nebula that is created at the working surface of the jet with the ISM.

Apart from the Crab pulsar (see §3), there is little evidence for jets from radio pulsars at other wavelengths, despite some concerted searches for them. In particular, at radio wavelengths the regions around numerous pulsars have
been mapped using the VLA [13], with no convincing for jets, except for PSR B1610−50 in the supernova remnant (SNR) Kes 32 [48]. Maps at 843 MHz show a well collimated (though thermal, non-polarised) jet emerging from the SNR and then spreading into a wide plume. Only the main part of the remnant is detected at X-ray wavelengths [38]. Many deep optical images have been obtained in order to study emission from the pulsars or their companions. The only pulsar (other than the Crab) with a candidate optical jet is PSR B0540−69 [12]. This was obtained with HST and is seen as a weak double sided linear feature lying across the pulsar in an Hα light.

3 Crab Pulsar and Nebula

With no fewer than three jets the Crab pulsar must be considered to be as bizarre as the other Galactic jet sources such at SS433 and GRO J1655−40. The three jets will be referred to as southeast, northwest and north.

A ROSAT image of the inner Crab nebula [3], confirmed the presence of the torus [11] and revealed a bright jet southeast of the pulsar. This jet appears to be aligned with the spin axis and is perpendicular to the plane of the torus [29] indicating the presence of collimated relativistic particles from the poles. With increasing distance from the pulsar, it becomes wider and bends southward. Wide field ground based images reveal a very similar but slightly more extended structure in line free optical continuum light. High resolution HST images in a similar band reveal two knots at 1,400 AU and 10,000 AU from the pulsar due to shocks in the inner jet [29]. Future images of a similar quality and resolution should allow the measurement of the proper motion of the knots, giving some indication of the velocity of the jet. The VLA map of Bietenholz and Kronberg [5] shows no evidence for a corresponding radio jet.

A similar but less well defined X-ray structure in the opposite (northwest) direction is interpreted as material compressed by the counter jet. In the optical images there are several features which run parallel to the edges of the counter jet. From a comparison of images taken at different epochs these have been shown to have proper motions perpendicularly away from the jet [29]. Again in the radio maps, there is no evidence for a radio counter jet [5].

A third unrelated, jet in a northerly direction, associated with the Crab nebula was found in a deep optical IIIaJ plate [56], although it was also present on isophote drawings [59]. The jet was detected in the emission lines OIII, Hα and NII, indicating that it has a non-thermal origin [25]. It is clearly present in radio maps made with the VLA [57,20]. The jet is highly polarised and non-thermal with the local magnetic field lines running parallel to the jet [58,5]. Recent proper motion measurements by Fesen and Staker [18] and Marcelin
et al. [45] are consistent with less precise earlier results and show that the jet is expanding along its length at 2500 km s\(^{-1}\) and perpendicular to its length at 260 km s\(^{-1}\). Using these velocities and the present jet size suggest that it formed around the same time as the pulsar. Unlike the other jets, this jet does not appear to be replenished by the pulsar.

4 Progenitors and Products

The discovery of the first millisecond pulsar B1937+21 [6], immediately led to a range of formation models (see Bhattacharya and van den Heuvel, [9] for a review). Low mass X-ray binaries (LMXBs) were among the proposed progenitors and their high incidence in globular clusters provoked several very successful searches of globular clusters for millisecond pulsars [41,31]. This provides an excellent example of how careful consideration of the evolution of a class of objects can yield methods of finding many more. The progenitors of these LMXBs are thought to be pulsars with low mass main sequence stellar companions, though rather surprisingly no such objects have been discovered. Since several candidates for relativistic Galactic jet sources are associated with LMXBs, pulsars are therefore potentially both their progenitors and products.

For high mass binary systems, a similar evolutionary picture has emerged in which a binary system containing a neutron star and a mass main sequence results from the first supernova explosion [9]. While the companion is still on the main sequence, the neutron star may be visible as a pulsar and two such objects are known, PSRs B1259−63 [32] and J0045−7319 [37]. When the companion evolves, these systems may form high mass X-ray binaries (HMXBs), some of which are also thought to harbour relativistic jets. When the second supernova occurs, either two solitary neutron stars are formed, or a more exciting dual neutron star binary in a relativistic orbit is formed, which can be used for tests of relativity [55]. Another possibility is the formation of a neutron star black hole binary, although no such objects have been found to date.

Lyne and Lorimer [43] recently demonstrated that the mean birth velocity of radio pulsars is 450 km s\(^{-1}\). The rotational axis of the B star in the PSR J0045−7319 system has recently been shown to be inclined to the orbital plane, giving rise to spin-orbit coupling and precession of the eccentric pulsar orbit [36]. This has provided independent evidence for a substantial neutron star birth kick. In general therefore, HMXBs, including those with jets might also be expected to have their orbital and spin angular momenta misaligned. At its last periastron passage in January 1994, PSR B1259−63 revealed some remarkable interactions with its Be star companion, including the disappearance of the pulsar, huge dispersion measure and rotation measure variations,
spin-up of the pulsar due to accretion and a continuum source possibly due to a wind interaction or jet [33,30]. Recent X-ray observations are more easily explained by the wind interaction model [34].

5 Conclusions

There appears to be significant evidence that isolated pulsars or neutron stars can produce jets, though none of these appear to be relativistic. There are many exciting prospects, particularly in the X-ray band. The existence of 3 jets associated with the Crab pulsar and nebula seems to be well established. Two of these jets are clearly associated with the pulsar and lie along its spin axis. Binary radio pulsars are likely to be both progenitors and products of Galactic jet sources in X-ray binaries and all of these systems are likely to have their spin and orbital angular momenta misaligned.

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