

1 **Multiwavelength monitoring of the enigmatic**
 2 **Narrow-Line Seyfert 1 PMN J0948+0022 in March-July 2009**

3 A. A. Abdo^{2,3}, M. Ackermann⁴, M. Ajello⁴, M. Axelsson^{5,6}, L. Baldini⁷, J. Ballet⁸,
 4 G. Barbiellini^{9,10}, D. Bastieri^{11,12}, B. M. Baughman¹³, K. Bechtol⁴, R. Bellazzini⁷,
 5 B. Berenji⁴, E. D. Bloom⁴, E. Bonamente^{14,15}, A. W. Borgland⁴, J. Bregeon⁷, A. Brez⁷,
 6 M. Brigida^{16,17}, P. Bruel¹⁸, T. H. Burnett¹⁹, G. A. Caliandro^{16,17}, R. A. Cameron⁴,
 7 P. A. Caraveo²⁰, J. M. Casandjian⁸, E. Cavazzuti²¹, C. Cecchi^{14,15}, Ö. Çelik^{22,23,24},
 8 A. Celotti²⁵, A. Chekhtman^{2,26}, J. Chiang⁴, S. Ciprini^{14,15}, R. Claus⁴, J. Cohen-Tanugi²⁷,
 9 W. Collmar²⁸, J. Conrad^{29,6,30}, L. Costamante⁴, S. Cutini²¹, A. de Angelis³¹,
 10 F. de Palma^{16,17}, E. do Couto e Silva⁴, P. S. Drell⁴, D. Dumora^{32,33}, C. Farnier²⁷,
 11 C. Favuzzi^{16,17}, S. J. Fegan¹⁸, W. B. Focke⁴, P. Fortin¹⁸, L. Foschini^{34,1}, M. Frailis³¹,
 12 L. Fuhrmann³⁵, Y. Fukazawa³⁶, S. Funk⁴, P. Fusco^{16,17}, F. Gargano¹⁷, N. Gehrels^{22,37},
 13 S. Germani^{14,15}, N. Giglietto^{16,17}, F. Giordano^{16,17}, M. Giroletti³⁸, T. Glanzman⁴,
 14 G. Godfrey⁴, I. A. Grenier⁸, J. E. Grove², L. Guillemot^{32,33}, S. Guiriec³⁹, Y. Hanabata³⁶,
 15 E. Hays²², R. E. Hughes¹³, M. S. Jackson^{29,6,40}, G. Jóhannesson⁴, A. S. Johnson⁴,
 16 W. N. Johnson², M. Kadler^{41,23,42,43}, T. Kamae⁴, H. Katagiri³⁶, J. Kataoka^{44,45},
 17 N. Kawai^{44,46}, M. Kerr¹⁹, J. Knödseder⁴⁷, M. L. Kocian⁴, M. Kuss⁷, J. Lande⁴,
 18 L. Latronico⁷, F. Longo^{9,10}, F. Loparco^{16,17}, B. Lott^{32,33}, M. N. Lovellette², P. Lubrano^{14,15},
 19 G. M. Madejski⁴, A. Makeev^{2,26}, W. Max-Moerbeck⁴⁸, M. N. Mazziotta¹⁷,
 20 W. McConville^{22,37}, J. E. McEnery²², S. McGlynn^{40,6}, C. Meurer^{29,6}, P. F. Michelson⁴,
 21 W. Mitthumsiri⁴, T. Mizuno³⁶, A. A. Moiseev^{23,37}, C. Monte^{16,17}, M. E. Monzani⁴,
 22 A. Morselli⁴⁹, I. V. Moskalenko⁴, I. Nestoras³⁵, P. L. Nolan⁴, J. P. Norris⁵⁰, E. Nuss²⁷,
 23 T. Ohsugi³⁶, N. Omodei⁷, E. Orlando²⁸, J. F. Ormes⁵⁰, D. Paneque⁴, D. Parent^{32,33},
 24 V. Pavlidou⁴⁸, V. Pelassa²⁷, M. Pepe^{14,15}, M. Pesce-Rollins⁷, F. Piron²⁷, T. A. Porter⁵¹,
 25 S. Rainò^{16,17}, R. Rando^{11,12}, M. Razzano⁷, A. Readhead⁴⁸, O. Reimer^{52,4}, T. Reposeur^{32,33},
 26 J. L. Richards⁴⁸, A. Y. Rodriguez⁵³, M. Roth¹⁹, F. Ryde^{40,6}, H. F.-W. Sadrozinski⁵¹,
 27 D. Sanchez¹⁸, A. Sander¹³, P. M. Saz Parkinson⁵¹, J. D. Scargle⁵⁴, C. Sgrò⁷, M. S. Shaw⁴,
 28 P. D. Smith¹³, G. Spandre⁷, P. Spinelli^{16,17}, M. S. Strickman², D. J. Suson⁵⁵,
 29 G. Tagliaferri³⁴, H. Tajima⁴, H. Takahashi³⁶, T. Tanaka⁴, J. B. Thayer⁴, J. G. Thayer⁴,
 30 D. J. Thompson²², L. Tibaldo^{11,8,12}, O. Tibolla⁵⁶, D. F. Torres^{57,53}, G. Tosti^{14,15},
 31 A. Tramacere^{4,58}, Y. Uchiyama^{59,4}, T. L. Usher⁴, V. Vasileiou^{22,23,24}, N. Vilchez⁴⁷,
 32 V. Vitale^{49,60}, A. P. Waite⁴, P. Wang⁴, A. E. Wehrle⁶¹, B. L. Winer¹³, K. S. Wood²,
 33 T. Ylinen^{40,62,6}, J. A. Zensus³⁵, M. Ziegler⁵¹ (The *Fermi*/LAT Collaboration)
 34 and
 35 E. Angelakis³⁵, C. Bailyn⁶³, H. Bignall⁶⁴, J. Blanchard⁶⁵, E. W. Bonning⁶³, M. Buxton⁶³,
 36 R. Canterna⁶⁶, A. Carramiñana⁶⁷, L. Carrasco⁶⁷, F. Colomer⁶⁸, A. Doi⁵⁹, G. Ghisellini³⁴,
 37 M. Hauser⁶⁹, X. Hong⁷⁰, J. Isler⁶³, M. Kino⁷⁸, Y. Y. Kovalev^{35,72}, Yu. A. Kovalev⁷²,

38 T. P. Krichbaum³⁵, A. Kuttyrev^{22,24}, A. Lahteenmaki⁷³, H. J. van Langevelde^{74,75},
39 M. L. Lister⁷⁶, D. Macomb⁷⁷, L. Maraschi³⁴, N. Marchili³⁵, H. Nagai⁷⁸, Z. Paragi^{74,79},
40 C. Phillips⁸⁰, A. B. Pushkarev^{35,81,82}, E. Recillas⁶⁷, P. Roming⁸³, M. Sekido⁸⁴,
41 M. A. Stark⁸³, A. Szomoru⁷⁴, J. Tammi⁷³, F. Tavecchio³⁴, M. Tornikoski⁷³,
42 A. K. Tzioumis⁸⁰, C. M. Urry⁶³, S. Wagner⁶⁹

¹Corresponding author: L. Foschini, luigi.foschini@brera.inaf.it.

²Space Science Division, Naval Research Laboratory, Washington, DC 20375, USA

³National Research Council Research Associate, National Academy of Sciences, Washington, DC 20001, USA

⁴W. W. Hansen Experimental Physics Laboratory, Kavli Institute for Particle Astrophysics and Cosmology, Department of Physics and SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94305, USA

⁵Department of Astronomy, Stockholm University, SE-106 91 Stockholm, Sweden

⁶The Oskar Klein Centre for Cosmoparticle Physics, AlbaNova, SE-106 91 Stockholm, Sweden

⁷Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, I-56127 Pisa, Italy

⁸Laboratoire AIM, CEA-IRFU/CNRS/Université Paris Diderot, Service d'Astrophysique, CEA Saclay, 91191 Gif sur Yvette, France

⁹Istituto Nazionale di Fisica Nucleare, Sezione di Trieste, I-34127 Trieste, Italy

¹⁰Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy

¹¹Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy

¹²Dipartimento di Fisica "G. Galilei", Università di Padova, I-35131 Padova, Italy

¹³Department of Physics, Center for Cosmology and Astro-Particle Physics, The Ohio State University, Columbus, OH 43210, USA

¹⁴Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, I-06123 Perugia, Italy

¹⁵Dipartimento di Fisica, Università degli Studi di Perugia, I-06123 Perugia, Italy

¹⁶Dipartimento di Fisica "M. Merlin" dell'Università e del Politecnico di Bari, I-70126 Bari, Italy

¹⁷Istituto Nazionale di Fisica Nucleare, Sezione di Bari, 70126 Bari, Italy

¹⁸Laboratoire Leprince-Ringuet, École polytechnique, CNRS/IN2P3, Palaiseau, France

¹⁹Department of Physics, University of Washington, Seattle, WA 98195-1560, USA

²⁰INAF-Istituto di Astrofisica Spaziale e Fisica Cosmica, I-20133 Milano, Italy

²¹Agenzia Spaziale Italiana (ASI) Science Data Center, I-00044 Frascati (Roma), Italy

²²NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

²³Center for Research and Exploration in Space Science and Technology (CRESTT), NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

²⁴University of Maryland, Baltimore County, Baltimore, MD 21250, USA

²⁵Scuola Internazionale Superiore di Studi Avanzati (SISSA), 34014 Trieste, Italy

²⁶George Mason University, Fairfax, VA 22030, USA

²⁷Laboratoire de Physique Théorique et Astroparticules, Université Montpellier 2, CNRS/IN2P3, Montpellier, France

²⁸Max-Planck Institut für extraterrestrische Physik, 85748 Garching, Germany

²⁹Department of Physics, Stockholm University, AlbaNova, SE-106 91 Stockholm, Sweden

³⁰Royal Swedish Academy of Sciences Research Fellow, funded by a grant from the K. A. Wallenberg Foundation

³¹Dipartimento di Fisica, Università di Udine and Istituto Nazionale di Fisica Nucleare, Sezione di Trieste, Gruppo Collegato di Udine, I-33100 Udine, Italy

³²Université de Bordeaux, Centre d'Études Nucléaires Bordeaux Gradignan, UMR 5797, Gradignan, 33175, France

³³CNRS/IN2P3, Centre d'Études Nucléaires Bordeaux Gradignan, UMR 5797, Gradignan, 33175, France

³⁴INAF Osservatorio Astronomico di Brera, I-23807 Merate, Italy

³⁵Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

³⁶Department of Physical Sciences, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan

³⁷University of Maryland, College Park, MD 20742, USA

³⁸INAF Istituto di Radioastronomia, 40129 Bologna, Italy

³⁹University of Alabama in Huntsville, Huntsville, AL 35899, USA

⁴⁰Department of Physics, Royal Institute of Technology (KTH), AlbaNova, SE-106 91 Stockholm, Sweden

⁴¹Dr. Remeis-Sternwarte Bamberg, Sternwartstrasse 7, D-96049 Bamberg, Germany

⁴²Erlangen Centre for Astroparticle Physics, D-91058 Erlangen, Germany

⁴³Universities Space Research Association (USRA), Columbia, MD 21044, USA

⁴⁴Department of Physics, Tokyo Institute of Technology, Meguro City, Tokyo 152-8551, Japan

⁴⁵Waseda University, 1-104 Totsukamachi, Shinjuku-ku, Tokyo, 169-8050, Japan

⁴⁶Cosmic Radiation Laboratory, Institute of Physical and Chemical Research (RIKEN), Wako, Saitama 351-0198, Japan

⁴⁷Centre d'Étude Spatiale des Rayonnements, CNRS/UPS, BP 44346, F-30128 Toulouse Cedex 4, France

⁴⁸California Institute of Technology, Pasadena, CA 91125, USA

⁴⁹Istituto Nazionale di Fisica Nucleare, Sezione di Roma "Tor Vergata", I-00133 Roma, Italy

⁵⁰Department of Physics and Astronomy, University of Denver, Denver, CO 80208, USA

⁵¹Santa Cruz Institute for Particle Physics, Department of Physics and Department of Astronomy and Astrophysics, University of California at Santa Cruz, Santa Cruz, CA 95064, USA

⁵²Institut für Astro- und Teilchenphysik and Institut für Theoretische Physik, Leopold-Franzens-

Universität Innsbruck, A-6020 Innsbruck, Austria

⁵³Institut de Ciències de l’Espai (IEEC-CSIC), Campus UAB, 08193 Barcelona, Spain

⁵⁴Space Sciences Division, NASA Ames Research Center, Moffett Field, CA 94035-1000, USA

⁵⁵Department of Chemistry and Physics, Purdue University Calumet, Hammond, IN 46323-2094, USA

⁵⁶Max-Planck-Institut für Kernphysik, D-69029 Heidelberg, Germany

⁵⁷Institució Catalana de Recerca i Estudis Avançats (ICREA), Barcelona, Spain

⁵⁸Consorzio Interuniversitario per la Fisica Spaziale (CIFS), I-10133 Torino, Italy

⁵⁹Institute of Space and Astronautical Science, JAXA, 3-1-1 Yoshinodai, Sagami-hara, Kanagawa 229-8510, Japan

⁶⁰Dipartimento di Fisica, Università di Roma “Tor Vergata”, I-00133 Roma, Italy

⁶¹Space Science Institute, Boulder, CO 80301, USA

⁶²School of Pure and Applied Natural Sciences, University of Kalmar, SE-391 82 Kalmar, Sweden

⁶³Department of Astronomy, Department of Physics and Yale Center for Astronomy and Astrophysics, Yale University, New Haven, CT 06520-8120, USA

⁶⁴Curtin Institute for Radio Astronomy, Curtin University of Technology, Perth WA 6845, Australia

⁶⁵Department of Physics, University of Tasmania, Hobart Tasmania 7001, Australia

⁶⁶Department of Physics and Astronomy, University of Wyoming, Laramie, WY 82071, USA

⁶⁷Instituto Nacional de Astrofísica, Óptica y Electrónica, Tonantzintla, Puebla 72840, Mexico

⁶⁸Observatorio Astronómico Nacional, E-28803 Alcalá de Henares, Spain

⁶⁹Landessternwarte, Universität Heidelberg, Königstuhl, D 69117 Heidelberg, Germany

⁷⁰Shanghai Astronomical Observatory, Shanghai 200030, China

⁷¹Nagoya University, Department of Physics and Astrophysics, Chikusa-ku Nagoya 464-8602, Japan

⁷²Astro Space Center of the Lebedev Physical Institute, 117810 Moscow, Russia

⁷³Metsähovi Radio Observatory, Helsinki University of Technology TKK, FIN-02540 Kylmälä, Finland

⁷⁴Joint Institute for VLBI in Europe, 7990 AA Dwingeloo, Netherlands

⁷⁵Leiden Observatory, NL 2300 RA Leiden, Netherlands

⁷⁶Department of Physics, Purdue University, West Lafayette, IN 47907, USA

⁷⁷Department of Physics, Boise State University, Boise, ID 83725, USA

⁷⁸National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo, 181-8588, Japan

⁷⁹MPA Research Group for Physical Geodesy and Geodynamics, H-1585 Budapest, Hungary

⁸⁰Australia Telescope National Facility, CSIRO, Epping NSW 1710, Australia

ABSTRACT

Following the recent discovery of γ rays from the radio-loud narrow-line Seyfert 1 galaxy PMN J0948+0022 ($z = 0.5846$), we started a multiwavelength campaign from radio to γ rays, which was carried out between the end of March and the beginning of July 2009. The source displayed activity at all the observed wavelengths: a general decreasing trend from optical to γ -ray frequencies was followed by an increase of radio emission after less than two months from the peak of the γ -ray emission. The largest flux change, about a factor of about 4, occurred in the X-ray band. The smallest was at ultraviolet and near-infrared frequencies, where the rate of the detected photons dropped by a factor 1.6 – 1.9. At optical wavelengths, where the sampling rate was the highest, it was possible to observe day-scale variability, with flux variations up to a factor of about 3. The behavior of PMN J0948+0022 observed in this campaign and the calculated power carried out by its jet in the form of protons, electrons, radiation and magnetic field are quite similar to that of blazars, specifically of flat-spectrum radio quasars. These results confirm the idea that radio-loud narrow-line Seyfert 1 galaxies host relativistic jets with power similar to that of average blazars.

Subject headings: quasars: individual (PMN J0948+0022) – galaxies: active – gamma rays: observations – X-rays: galaxies – ultraviolet: galaxies – infrared: galaxies – radio continuum: galaxies

1. Introduction

The recent detection by *Fermi Gamma-ray Space Telescope* of γ rays from the radio-loud narrow-line Seyfert 1 galaxy (RL-NLS1) PMN J0948+0022¹ ($z = 0.5846$) opened new and

⁸¹Crimean Astrophysical Observatory, 98409 Nauchny, Crimea, Ukraine

⁸²Pulkovo Observatory, 196140 St. Petersburg, Russia

⁸³Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA

⁸⁴National Institute of Information and Communications Technology, Kashima Space Research Center, 893-1, Hirai, Kashima, Ibaraki, 314, Japan

¹We note that the absolute magnitude of this source is $M_B = -23.6$, so formally matches also the definition of quasars.

51 interesting questions on the unified model of active galactic nuclei (AGN), the development
 52 of relativistic jets and the evolution of radio-loud AGN (Abdo et al. 2009a, Foschini et al.
 53 2009a). Indeed, before *Fermi*/LAT (Large Area Telescope) it was known that γ rays from
 54 AGN are produced in blazars and radio galaxies, but we have to add also RL-NLS1s.

55 NLS1s are active nuclei similar to Seyferts, where the optical permitted lines emitted
 56 from the broad-line region (BLR) are narrower than usual, with $\text{FWHM}(\text{H}\beta) < 2000 \text{ km s}^{-1}$
 57 (see Pogge 2000, for a review). Other characteristics are $[\text{OIII}]/\text{H}\beta < 3$ and a bump of FeII,
 58 making them a peculiar class of AGN. NLS1s are different from Seyfert 2s, whose optical
 59 spectra typically display $\text{FWHM}(\text{H}\beta) < 1000 \text{ km s}^{-1}$, $[\text{OIII}]/\text{H}\beta > 3$ and no bump of FeII.
 60 NLS1s are also different from the naked AGN discovered by Hawkins (2004), a peculiar class
 61 of Seyferts without the BLR, which have $[\text{OIII}]/\text{H}\beta \gg 3$. Indeed, NLS1s do have both BLR
 62 and the narrow-line region (NLR), but the BLR emits only permitted lines narrower than in
 63 Seyfert 1s (Rodríguez-Ardila et al. 2000).

64 NLS1s are generally radio-quiet, but a small fraction of them ($< 7\%$, according to
 65 Komossa et al. 2006), are radio-loud. It is not clear how these sources fit into the framework
 66 of radio-loud AGN. Some studies of the average non-simultaneous multiwavelength properties
 67 (from radio to X-rays) of RL-NLS1s suggested some possibilities. Komossa et al. (2006)
 68 argued that RL-NLS1s could be some young stage of quasars, while Yuan et al. (2008) found
 69 some similarities to TeV BL Lacs, but having strong emission lines they would represent
 70 the so-called “high-frequency peaked flat-spectrum radio quasars” conjectured by Padovani
 71 (2007). Foschini et al. (2009b) found instead that there is no one-to-one correlation of RL-
 72 NLS1s properties with any specific type of blazar or radio galaxy. In some cases, there are
 73 similarities with flat-spectrum radio quasars, while others are like BL Lacs.

74 Now, the first detection by *Fermi*/LAT of γ rays from one RL-NLS1 - namely PMN
 75 J0948+0022 - sets the definitive confirmation of the presence of a relativistic jet in these
 76 sources. The discovery of γ -ray emission from other sources of this type (Abdo et al.,
 77 in preparation) raise RL-NLS1s to the rank of γ -ray emitting AGN. However, any average
 78 spectral energy distribution (SED) of a γ -ray loud AGN leaves open several important ques-
 79 tions on the mechanisms of radiation emission, such as whether the synchrotron self-Compton
 80 (SSC) or the external Compton (EC) production mechanism is dominant at high-energies
 81 and where the zone is where most of the dissipation occurs. Because PMN J0948+0022 is
 82 the first object of this new class of γ -ray AGN, it is important to observe it for a long time,
 83 in order to understand if there is something unexpected and if its behavior is very different
 84 from blazars and radio galaxies or not.

85 With these aims in mind, we decided to set up a multiwavelength campaign on this
 86 source. The campaign involved several space and ground-based facilities across the whole

87 electromagnetic spectrum, from radio to γ rays (in alphabetical order): ATOM (Landesstern-
 88 warte), F-GAMMA (Effelsberg), e-VLBI (EVN, LBA), *Fermi*, G. Haro Telescope (INAOE),
 89 Metsähovi, OVRO, RATAN-600, *Swift*, SMARTS, MOJAVE (VLBA), WIRO. The period
 90 covered was between 2009 March 24 and July 5. We measured variability at multiple wave-
 91 bands, modelled the resulting SEDs, and compared the results to those for more typical
 92 γ -ray blazars in the FSRQ and BL Lac classes.

93 Throughout this work, we adopted a Λ CDM cosmology from the most recent *WMAP*
 94 results, which give the following values for the cosmological parameters: $h = 0.71$, $\Omega_m = 0.27$,
 95 $\Omega_\Lambda = 0.73$ and with the Hubble-Lemaître constant $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Komatsu et
 96 al. 2009).

97 2. Data Analysis

98 2.1. Fermi/LAT

99 The data from the Large Area Telescope (LAT, Atwood et al. 2009) were analyzed using
 100 the same procedures outlined in Abdo et al. (2009a), but with a more recent version of the
 101 software (`Science Tools v 9.15.2`), Instrument Response Function (`IRF_P6_V3_DIFFUSE`,
 102 Rando et al. 2009) and background². Photons with energy above 100 MeV and between
 103 MJD 54910 (2009 March 20) and 55017 (2009 July 5) were selected. The quoted 1σ errors
 104 of the analyses are statistical only and systematic errors should be added. The most recent
 105 estimates set these values as 10% at 100 MeV, 5% at 500 MeV and 20% at 10 GeV (Rando
 106 et al. 2009).

107 The result of the fit with a power-law model in the form $F(E) \propto E^{-\Gamma}$ to the data inte-
 108 grated over the whole campaign gives an average flux ($E > 100 \text{ MeV}$) equal to $(1.5 \pm 0.1) \times$
 109 $10^{-7} \text{ ph cm}^{-2} \text{ s}^{-1}$, a photon index $\Gamma = 2.48 \pm 0.09$ with Test Statistic $TS = 337$ (which is
 110 roughly equivalent to 18σ , since $\sigma \sim \sqrt{TS}$; see Mattox et al. 1996 for the definition of TS).
 111 Comparison with the values obtained from the fit of the first 5 months of data, reported in
 112 Abdo et al. (2009a) and recalculated here as $F_{E>100\text{MeV}} = (1.6 \pm 0.1) \times 10^{-7} \text{ ph cm}^{-2} \text{ s}^{-1}$
 113 with $\Gamma = 2.7 \pm 0.1$ ($TS = 386$), shows no changes in the average flux, but a slight spec-
 114 tral hardening during the present multiwavelength campaign. We observed no emission for
 115 energies above $\sim 2 \text{ GeV}$.

116 PMN J0948+0022 shows some variability on shorter timescales (Fig. 1), but the weak-

²Everything now publicly available at: <http://fermi.gsfc.nasa.gov/ssc/data/>

ness of the γ -ray flux hampers the study of the changes of its properties. Therefore, we decided to divide the campaign into three larger bins, by integrating and analyzing data month-by-month. The results are summarized in Table 1. The better statistics allow us to measure a clear drop in flux of a factor ~ 2 from April to May and June, with a corresponding hardening of the spectral slope. We also note that the 2009 April flux was higher than the average flux in 2008 August-December.

2.2. Swift (BAT, XRT, UVOT)

The *Swift* satellite (Gehrels et al. 2004) observed PMN J0948+0022 11 times, starting on MJD 54916.26 (2009 March 26 06:21 UTC) and ending on MJD 55015.53 (2009 July 3 12:41 UTC), with average exposures of ≈ 5 ks for each observation. Data of BAT (Barthelmy et al. 2005), XRT (Burrows et al. 2005) and UVOT (Roming et al. 2005) have been analyzed by means of the HEASoft v. 6.6.3 software package, with default parameters (except as specified below) and the calibration database updated on 2009 June 5.

No detection was found with BAT in the hard X-ray energy band, after having integrated all the available data obtained in this campaign (total exposure 55.6 ks, including the observation performed on 2008 December 5, see Abdo et al. 2009a), with an upper limit (3σ) of 3.2×10^{-10} erg cm $^{-2}$ s $^{-1}$ in the 20 – 100 keV energy band.

XRT was set to work in photon counting mode. Photons in the 0.2 – 10 keV energy band and with grades 0-12 (single to quadruple pixels events) were selected. A check for pile-up gave negative results. The extracted spectrum was rebinned to have a minimum of 30 counts per bin, in order to apply the χ^2 statistical test. In one case (ObsID 00031306006) the exposure was lower than expected (1.4 ks) and it was necessary to use the Cash statistical test (Cash 1979), which allows parameters estimation in low counts measurements through the likelihood ratio. The spectra were fitted with a power-law model with Galactic absorption (5.22×10^{22} cm $^{-2}$, Kalberla et al. 2005) and the results are summarized in Table 2 and Fig. 1.

UVOT counts in all the 6 available filters (V, B, U, UVW1, UVM2, UVW2) were extracted from a source region radius of $5''$ and a background region with radius $1'$, centered in a nearby source-free region and not in an annulus region around the source because of nearby contaminating sources. The observed magnitudes were corrected for the Galactic absorption $A_V = 0.277$ mag. The absorption for the other filters was calculated according to the extinction laws of Cardelli et al. (1989). The dereddened magnitudes were converted into fluxes in physical units taking into account the zeropoints by Poole et al. (2008). Data

150 are displayed in Fig. 2 and 3.

151 We note that the optical/IR filters bandpasses of the several facilities employed in this
152 research (UVOT and the other ground-based telescopes ATOM, SMARTS, INAOE, WIRO
153 described in the next Sections) do not match exactly. However, after a careful inspection of
154 simultaneous or quasi-simultaneous observations, we found that these mismatches in filter
155 bandpasses are negligible because they are smaller than the error bars.

156 We note also that at all the UV/optical/NIR wavelengths the quasar is unresolved with
157 no hint of a contribution from starlight of the underlying galaxy.

158 **2.3. Automatic Telescope for Optical Monitoring for H.E.S.S. (ATOM)**

159 Optical observations in Johnson R and B filters for this campaign were obtained between
160 March 27 and May 20 with the 0.8 m optical telescope ATOM in Namibia. ATOM is operated
161 robotically by the H.E.S.S. collaboration and obtains automatic observations of confirmed
162 or potential γ -bright blazars. Data analysis (debiassing, flat fielding, photometry using
163 **SExtractor**; Bertin & Arnouts, 1996) is conducted automatically. The magnitudes were
164 then corrected for galactic extinction using the extinction laws of Cardelli et al. (1989),
165 assuming $R_V = 3.1$ and $A_V = 0.277$ mag, which gives an absorption of $A_B = 0.37$ mag and
166 $A_R = 0.23$ mag. The magnitudes were converted in fluxes using the zeropoints of Bessell
167 (1979). Data are shown in Fig. 3.

168 **2.4. Small and Moderate Aperture Research Telescope System (SMARTS)**

169 The source was monitored at the Cerro Tololo Inter-American Observatory (CTIO)
170 SMARTS 1.3 m telescope plus ANDICAM, which is a dual-channel imager with a dichroic
171 linked to an optical CCD and an IR imager, from which it is possible to obtain simultaneous
172 data from 0.4 to 2.2 μm . Optical/Near-Infrared (NIR) observations with the filters B, R and
173 J were carried out between 2009 June 1 and 14 (MJD 54983-54996).

174 Optical data were bias-subtracted, overscan-subtracted, and flat-fielded using the **ccdproc**
175 task in **IRAF**. The optical photometry was calibrated absolutely using published magnitudes
176 (from the USNO-B1.0 catalogue) of secondary standard stars in the field of the object. IR
177 data were sky-subtracted, flat-fielded, and dithered images combined using in-house **IRAF**
178 scripts. The IR photometry was absolutely calibrated using 2MASS magnitudes of a sec-
179 ondary standard star. We estimated photometric errors by calculating the 1σ variation in
180 magnitude of comparison stars with comparable magnitude to PMN J0948 + 0022 in the

181 same frame. The results are summarized in Fig. 3 and 4.

182 2.5. Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE)

183 NIR observations of PMN J0948+0022 were done between 2009 April 3 and June 21,
184 at the 2.1 m telescope “Guillermo Haro”, with the NIR camera “CANICA”, equipped with a
185 Rockwell 1024×1024 pixel Hawaii infrared array, working at 75.4 K, with standard J(1.164
186 - 1.328 μm), H(1.485 - 1.781 μm) and K_s (1.944 - 2.294 μm) filters. The plate scale is 0.32
187 arcsec/pix. Observations were carried out in series of 10 dithered frames in each filter. A
188 proper number of additional observations were adopted for the K_s observations. Data sets
189 were coadded after correcting for bias and flat-fielding. Flats were obtained from sky frames
190 derived from the dithered ones. Data are shown in Fig. 4.

191 2.6. University of Wyoming Infrared Observatory (WIRO)

192 The NIR observations at WIRO of PMN J0948+0022 were obtained on 2009 May 8-9,
193 as part of a blazar observing campaign in which selected AGN are monitored over timescales
194 of months, once the AGN is measured by the LAT to exceed a nominal threshold of $15 \times$
195 10^{-8} ph cm^{-2} s^{-1} ($E > 100$ MeV). The NIR camera is sited on the Wyoming Infrared
196 Observatory’s 2.3 m telescope, which is optimized for IR observations, and located on Mt.
197 Jelm at an elevation of 2943 m. The detector is a professional grade 256^2 InSb chip – a
198 spare from the *Spitzer* mission – with a square $100''$ field of view. Once accounting for
199 atmospheric absorption, the camera’s J (1.171 – 1.328 μm) and K (1.987 – 2.292 μm) filters
200 have bandpasses and center wavelengths very similar to the MKO-NIR system (Tokunaga
201 & Vacca 2005).

202 The observations of PMN J0948+0022 were made on 2009 May 8-9: sixteen 26 s integra-
203 tions each in the J and K filters, per night. Each set of frames was flat-fielded and reviewed
204 for transparency – with maximum of three frames per set discarded – and the remaining
205 retained frames stacked in registration. The source fluxes were then compared with fluxes of
206 same or near-frame stars as well as with fluxes of NIR Arnica³ standards stars which were
207 also obtained with the NIR camera, to derive J and K magnitudes. Data are shown in
208 Fig. 4.

³see Table 2 in L. Hunt et al., Arcetri Technical Report no. 3, 1994:
<http://www.arcetri.astro.it/irlab/instr/arnica/arnica.html>

2.7. Owens Valley Radio Observatory (OVRO)

PMN J0948+0022 has been observed regularly between 2009 March 26 and July 3, at 15 GHz by the Owens Valley Radio Observatory (OVRO) 40 m telescope as part of an ongoing *Fermi* blazar monitoring program. Flux densities were measured using azimuth double switching as described in Readhead et al. (1989). The relative uncertainties in flux density result from a 5 mJy typical thermal uncertainty in quadrature with a 1.6% non-thermal random error contribution. The absolute flux density scale is calibrated to about 5% using the Baars et al. model for 3C 286 (Baars et al. 1977). This absolute uncertainty is not included in the plotted errors. The light curve is shown in Fig. 5.

2.8. Metsähovi

The 37 GHz observations were made between 2009 April 10 and May 30, with the 13.7 m diameter Metsähovi radio telescope, which is a radome enclosed paraboloid antenna situated in Finland. A typical integration time to obtain one flux density data point is 1200 – 1400 s. The detection limit of our telescope at 37 GHz is on the order of 0.2 Jy under optimal conditions. Data points with a signal-to-noise ratio < 4 are handled as non-detections.

The flux density scale is set by observations of DR 21. Sources 3C 84 and 3C 274 are used as secondary calibrators. A detailed description on the data reduction and analysis is given in Teräsranta et al. (1998). The error estimate in the flux density includes the contribution from the background and the uncertainty of the absolute calibration. The light curve is shown in Fig. 5.

2.9. RATAN-600

The 2 – 22 GHz instantaneous radio spectrum of PMN J0948+0022 was observed two times, on 2009 March 24 and 25, with the 600-meter ring radio telescope RATAN-600 (Korolkov & Parijskij 1979) of the Special Astrophysical Observatory, Russian Academy of Sciences, located in Zelenchukskaya, Russia. The broad-band radio continuum spectrum was measured quasi-simultaneously (within several minutes) in a transit mode at five different bands. Details on the method of observation, data processing, and amplitude calibration are described in Kovalev et al. (1999). The presented data were collected using the Northern ring sector of RATAN-600. Averaged flux density spectrum is presented in Fig. 6.

2.10. F-GAMMA (Effelsberg)

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239 The radio spectrum of PMN J0948+0022 at centimeter wavelength was measured with
 240 the Effelsberg 100 m telescope, within the project F-GAMMA, the monitoring program of
 241 *Fermi* γ -ray blazars (F-GAMMA project, Fuhrmann et al. 2007). The observations were
 242 performed at different epochs (from 2009 April 13 to June 27), with the secondary focus
 243 heterodyne receivers between 2.64 and 42 GHz, and quasi-simultaneously with cross-scans,
 244 that is slewing over the source position, in azimuth and elevation direction, with adaptive
 245 numbers of sub-scans in order to reach the required sensitivity (for details, see Fuhrmann
 246 et al. 2008; Angelakis et al. 2008). Pointing off-set correction, gain correction, atmospheric
 247 opacity correction and sensitivity correction have been applied to the data. The results are
 248 summarized in Fig. 6.

2.11. Monitoring Of Jets in Active galactic nuclei with VLBA Experiments (MOJAVE)

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251 PMN J0948+0022 was observed on 2009 May 28 within the framework of the program
 252 MOJAVE, which is a survey with the Very Large Baseline Array (VLBA) at 15.4 GHz aiming
 253 at the study of the parsec-scale structure of relativistic jets in sources with declination $> -30^\circ$
 254 (Lister et al. 2009). Total intensity and linear polarization were measured (Fig. 7). The
 255 total integrated flux density is $S_{\text{VLBA}} = 437$ mJy (peak value: 425 mJy/beam), while the
 256 integrated linear polarization is 3.5 mJy (peak value: 3.6 mJy/beam). The relative error in
 257 both cases is about 5%. For details of data processing we refer to Lister et al. (2009) and
 258 Lister & Homan (2005).

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These observations were performed with a 512 Mbps recording rate and resulted in a
 very high dynamic range (about 8,000:1) parsec-scale total intensity image. The structure
 was modeled using three components with circular Gaussian intensity profiles. It was found
 that the VLBA core highly dominates the emission and is unresolved: the core flux density
 $S_{\text{core}} = 420$ mJy covers 96% of the total parsec-scale emission. We estimated an upper
 limit of the core size following Kovalev et al. (2005), which turned out to be $\theta_{\text{core}} < 60 \mu\text{as}$
 (confidence level $> 99\%$). We are able to get such a small upper limit, because of the high
 dynamic range and the simplicity of the source structure. The core brightness temperature
 in the source frame is estimated to be greater than 1.0×10^{12} K.

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The object is highly compact in comparison to the sample of radio-loud AGN reported
 by Lister & Homan (2005). Its core-to-jet flux density ratio is about 25, well above the
 average value of 3 in the sample. However, the 0.7% fractional linear polarization of the

271 structure is in agreement with the average distribution of bright quasars (Lister & Homan
272 2005).

273 Another MOJAVE observation was performed after the end of the campaign (2009 July
274 23, not shown here⁴), revealing that the flux density at 15 GHz was already decreasing
275 ($S_{\text{VLBA}} = 340$ mJy), and the parsec-scale core appeared to be fainter than in 2009 May.

276 2.12. e-VLBI

277 PMN J0948+0022 was observed with the e-VLBI (electronic Very Long Baseline Inter-
278 ferometry) technique on April 21 at 1.6 GHz, and on May 23, Jun 10, and July 4 at 22 GHz.
279 The epoch at 1.6 GHz was a pilot observation, lasting about 80 minutes with EVN (Euro-
280 pean VLBI Network) stations only. In the following epochs, EVN telescopes were joined by
281 Australian and Japanese antennas, for about 9 hours at each epoch with about 1 hour of
282 mutual visibility between Europe, Asia, and Australia (except in the last epoch).

283 Real time fringes were detected in all baselines between participating telescopes at all
284 epochs. This includes Europe-Australia baselines as long as 12000 km, which reveals that
285 the source is highly compact and allows us to constrain its angular size. From visibility
286 model fitting to the first 22 GHz epoch, we determine an upper limit to the core size of
287 0.2 mas. This corresponds to a lower limit for the brightness temperature of $T_B > 2.9 \times 10^{10}$
288 K, and is consistent with the result from the second 22 GHz epoch and the 15 GHz data
289 from MOJAVE. The 1.6 GHz observation and the final 22 GHz one lacked Europe-Australia
290 baselines, resulting in less tight constraints. Also, the source shows an inverted spectrum
291 between 1.6 and 22 GHz, being only 0.17 Jy at 1.6 GHz and 0.41 Jy at 22 GHz (weighted
292 average), with a spectral index of -0.3 ($S_\nu \propto \nu^{-\alpha}$).

293 Extended emission is not revealed within our noise levels of about 1 mJy/beam. The
294 elongation of the fitted Gaussian is roughly along the extended emission seen at 15 GHz,
295 but the extended emission is resolved out in these maps. Further details on the observations
296 and a higher level analysis will be presented in a forthcoming publication (Giroletti et al.,
297 in preparation). The results are summarized in Table 3.

⁴See <http://www.physics.purdue.edu/astro/MOJAVE/sourcepages/0946+006.shtml>

3. Spectral Energy Distributions (SEDs)

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299 We have built optical-to- γ rays SED by picking time intervals so that they would be
 300 centered on the epoch of the *Swift* observations (see Table 2). We used the data from *Swift*
 301 XRT and UVOT, and, when available, the optical/NIR data from ground-based facilities⁵.
 302 In the case of γ rays, we adopted an integration time of 5 days, centered on the day of the
 303 *Swift* snapshot. The integrated LAT data were analyzed in two energy bands (0.1 – 1 and
 304 1 – 10 GeV) and we have taken as detections those with $TS \geq 9$. We have also re-built
 305 the SED corresponding to the *Swift* observation performed on 2008 December 5, which was
 306 reported in Abdo et al. (2009a). However, this time, we used for LAT the data integrated
 307 over 5 days (instead of 5 months). The 12 SEDs are displayed in Fig. 8.

308 We have modeled these SEDs with the synchrotron and inverse-Compton (IC) model,
 309 which is described in detail in Ghisellini & Tavecchio (2009) and was also used in the previous
 310 study (Abdo et al. 2009a). For the sake of simplicity, we just recall some basic definitions
 311 and symbols used in the present work.

312 The emitting blob of plasma has spherical shape with size r and is located at a distance
 313 R_{diss} from the central spacetime singularity with mass $M = 1.5 \times 10^8 M_{\odot}$ (see Abdo et al.
 314 2009a), moving with constant bulk Lorentz factor $\Gamma_{\text{bulk}} = 10$.

315 The energy distribution of the injected relativistic electrons has a broken power-law
 316 model, with shapes defined by $\gamma_e^{-s_1}$ and $\gamma_e^{-s_2}$, below and above $\gamma_{e,\text{break}}$, respectively, where γ_e
 317 is the random Lorentz factor of electrons. This input distribution is then modified according
 318 to the radiative cooling occurring during a finite time of injection (the light crossing time
 319 of the blob) and the possibility of pair production through $\gamma\gamma \rightarrow e^{\pm}$. The distribution in
 320 output is then used to generate the observed radiation through the synchrotron, synchrotron
 321 self-Compton (SSC) and external-Compton (EC) processes. The seed photons for EC are
 322 generated directly by the accretion disk and its X-ray corona, the broad-line region (BLR),
 323 and the infrared torus.

324 Obviously, in this case, the BLR emits only narrow-lines, but what is important with
 325 respect to EC is the energy density in the comoving frame. As already outlined in Abdo et
 326 al. (2009a), the differences of the BLR in NLS1s are thought to be due to (1) a disk-like
 327 shape of the BLR (Decarli et al. 2008) or (2) a shift of the BLR farther from the central
 328 supermassive singularity due to the radiation pressure of the highly accreting disk (Marconi

⁵Radio data were not used in the fit of the SEDs, because they are generated in regions external to that where optical-to- γ rays are produced. More details on radio observations will be presented in Giroletti et al. (in preparation).

329 et al. 2008). From the point of view of generating seed photons for EC, in case (1) there is
 330 no difference from a shell-like shape of the BLR, since what is important is the angle with
 331 which the blob sees the BLR (see angles α_1 and α_2 in Fig. 1 of Ghisellini & Tavecchio 2009).
 332 In case (2), we performed some tests by pushing the BLR further out (up to 5×10^{17} cm),
 333 but we found minimal changes in the parameters. We note also that the size of the BLR
 334 is defined on the basis of the accretion disk luminosity, which in turn is measured from
 335 the SED, as $R_{\text{BLR}} = 10^{17} \sqrt{L_{\text{disk},45}}$, where $L_{\text{disk},45}$ is the luminosity of the disk in units of
 336 10^{45} erg s $^{-1}$.

337 The maximum electron energy is reached with $\gamma_{e,\text{max}}$, and that corresponding to the
 338 IC peak is $\gamma_{e,\text{peak}}$. The injected power in the form of relativistic electrons is L'_e (comoving
 339 frame), while the power carried out by the jet is composed of kinetic motion of electrons
 340 (L_e) and protons (L_p , one for each electron), radiation (L_{rad}) and magnetic field (L_B).

341 The summary of the 12 SED fits is reported in Table 4, while Fig. 9 and 10 display the
 342 evolution of some parameters on a time scale coordinated with those of the light curves of
 343 Figs. 1-5, to allow an easy comparison with observations.

344 We have also built an overall SED from the averages of all the data collected in this
 345 campaign (Fig. 11). It is not an average over the whole campaign, except for LAT data, which
 346 are collected daily. At all the other wavelengths, the result is an average of the available
 347 observations, generally limited to some periods in the campaign. The parameters obtained
 348 by the modeling of this overall SED are also reported in Table 4.

349 4. Discussion

350 An immediate comparison between the two average SEDs obtained from the present
 351 campaign (2009 March-July) and that of the period 2008 August-December analyzed in
 352 Abdo et al. (2009a), together with archival data (Fig. 11), displays some changes in the
 353 emission, more pronounced at some frequencies. An inspection of the multiwavelength light
 354 curves highlights variability both in flux (at all the observed frequencies; see Fig. 1-5) and
 355 spectral properties (Table 1, Fig. 6 and Fig. 12), except for X-rays, which show no variability
 356 in the photon index, despite showing the strongest flux variations.

357 To check for the presence of variability, we fitted the light curves at different frequencies
 358 with a constant flux light curve, but we got high values of reduced χ^2 , thus confirming that
 359 the source displayed some activity at all the wavelengths (Table 5). The most dramatic flux
 360 changes are in X-rays (factor 3.9), radio 37 GHz (factor 3.2) and optical V and R filters
 361 (factor 2.7 and 2.9, respectively), the latter with day timescales (Table 5). Interestingly,

362 a clear decreasing trend from X-rays to optical wavelengths is visible at the beginning of
 363 May and corresponds to a period with decreasing γ rays (Table 1). Although only a few
 364 observations are available between May 5 and 15, the drop in flux is consistent with an
 365 exponential decay of the form $F(t) = F(t_0) \exp[-(t - t_0)/\tau]$, with a decay constant $\tau \sim 7$
 366 days. The opposite occurs at radio and NIR frequencies, reaching a peak at 15 GHz about
 367 20 days after the beginning of the X-ray-to-optical flux decrease.

368 This coordinated trend is the typical behavior expected from the electromagnetic emis-
 369 sion of a relativistic jet. At the radio, optical and X-ray frequencies, there is a dominance
 370 of the synchrotron and synchrotron self-Compton (SSC) processes, while γ rays are gener-
 371 ated by external Compton (EC). This is also clear by looking at the change in the opti-
 372 cal/UV spectrum (Fig. 12). Indeed, it is known that these frequencies sample the rising
 373 part of the accretion disk bump, but before May 5 the optical/UV spectrum was flatter
 374 ($\alpha_{V-UVW2} = 0.08 \pm 0.06$) and at high fluxes⁽⁶⁾. This is likely due to a higher synchrotron
 375 emission, while the accretion disk had relatively small change. In the following ~ 10 days,
 376 the synchrotron emission decreased to its minimum, and the shape of the optical/UV emis-
 377 sion returned to being hard ($\alpha_{V-UVW2} = 0.4 \pm 0.2$) and mainly due to the rising part of the
 378 accretion disk bump. The X-ray emission followed this behavior, being due to SSC, i.e. it
 379 was high on May 5 and decreased to its minimum on May 15.

380 The radio emission, coming from zones farther away from the optical-to- γ rays dissipa-
 381 tion region, reached its peak about 20 days after the optical-to-X-ray drop, as shown in the
 382 light curves at 15 and 37 GHz (Fig. 5). However, the spectral index $\alpha_{5-15\text{GHz}}$, as measured
 383 between 4.85 and 14.6 GHz, changed well before, from a rather flat value ($\alpha_{5-15\text{GHz}} \sim 0$) on
 384 April 13 (MJD 54934.98) and earlier, to an inverted spectrum ($\alpha_{5-15\text{GHz}} = -0.40 \pm 0.03$)
 385 already on April 30 (MJD 54951.75) (about two weeks, see Fig. 6). On May 27 (MJD
 386 54978.79), close to the maximum flux, the spectral inversion was at its maximum too
 387 ($\alpha_{5-15\text{GHz}} = -0.98 \pm 0.05$) and then, on June 27 (MJD 55009.53), the spectral index was
 388 already returning to a flatter shape ($\alpha_{5-15\text{GHz}} = -0.77 \pm 0.04$). This is in agreement with
 389 the findings by Kovalev et al. (2009) with reference to the general radio vs γ -ray properties
 390 of the blazars detected by *Fermi*/LAT during the first three months of operation (Abdo et
 391 al. 2009b). They found that the time separation between γ -ray and radio flares is typically
 392 up to a few months, in agreement with the results obtained by other authors on individual
 393 sources studies (e.g. Raiteri et al. 2008, Larionov et al. 2008, Villata et al. 2009). In the
 394 present case, if we adopt as references the peak of the γ -ray emission that occurred in the
 395 first two weeks of 2009 April and the peak of the radio flux at 15 GHz that occurred in the

⁶Having defined $\alpha_{12} = -\log(F_1/F_2)/\log(\nu_1/\nu_2)$, where F_1 and F_2 are the fluxes at frequencies ν_1 and ν_2 .

396 second half of 2009 May, we can roughly estimate a delay of 1.5-2 months.

397 The modeling of the SED (Fig. 8, Table 4, see also the evolution of the model parameters
 398 in Fig. 9 and 10) confirmed this phenomenological view. During this campaign, the modelled
 399 values of the magnetic field, injected power, and the radius at which dissipation of energy
 400 occurs varied by factors of 2.4, 4.1 and 2.4, respectively. At the same time, the power in
 401 radiation, electrons, protons, and the magnetic field varied by 4.4, 3, 4.2 and 1.2, respectively.
 402 The dissipation radius was $(3.6 - 8.8) \times 10^{16}$ cm, roughly 0.04 – 0.091 light years or 0.012 –
 403 0.028 pc from the central supermassive black hole. At the beginning of May, when the
 404 synchrotron and SSC emission dominate the optical-to-X-ray emission, the dissipation region
 405 is very compact and the magnetic field is high. The trend of the injected power (flagged
 406 by the γ -ray emission) is decreasing. Then, on May 15, the dissipation radius is larger
 407 together with a smaller value of the magnetic field. We note that the accretion remained
 408 almost constant, at about 40-50% of the Eddington value⁷.

409 The fit from the “overall” SED (Table 4) had the following values: the dissipation
 410 radius is 67.5×10^{15} cm, $L_{\text{disk}} = 0.5$ times the Eddington luminosity, the injected power is
 411 2.3×10^{43} erg s⁻¹, while the power carried out by the jet is 1.5×10^{46} erg s⁻¹ in protons,
 412 2.9×10^{44} erg s⁻¹ in electrons, 2.1×10^{45} erg s⁻¹ in radiation, and 2.8×10^{44} erg s⁻¹ in
 413 the magnetic field. These values are well within the range of typical values for other γ -ray
 414 blazars (cf Celotti & Ghisellini 2008, Ghisellini et al. 2009).

415 5. Conclusions

416 We thus confirm that PMN J0948+0022 – despite being a radio-loud narrow-line Seyfert
 417 1 – hosts a relativistic γ -ray emitting jet, similar to those of FSRQs, and confirms all the
 418 hypotheses adopted to model the non-simultaneous SED in Abdo et al. (2009a). This
 419 type of source can develop a relativistic jet like blazars and radio galaxies, even though the
 420 conditions of the environment close to its central spacetime singularity are quite different.
 421 This is indeed a new class of γ -ray emitting AGN.

422 We have shown that the variability at multiple wavebands and the physical parameters
 423 resulting from modelling the SEDs are typical of a source midway between FSRQs and BL
 424 Lacs. The calculated powers carried by the various components of the jet are low compared
 425 to the distributions of values for FSRQ, but above those of BL Lacs (cf Celotti & Ghisellini

⁷The Eddington value of the accretion disk luminosity corresponds to the power emitted in a condition of equilibrium between the force due to the radiation pressure and the gravity.

2008, Ghisellini et al. 2009), and therefore within the average range of blazar powers, despite the relatively low mass of its black hole, $1.5 \times 10^8 M_{\odot}$ (Abdo et al. 2009a). The γ -ray observations performed to date have not revealed very high fluxes, i.e. above the usual threshold adopted to define an outburst in normal blazars ($F_{E>100\text{MeV}} > 10^{-6}$ ph cm $^{-2}$ s $^{-1}$). However, it is not clear yet if this is due to the duty cycle of this source – and hence if we have just observed a minor event – or if the different environmental conditions in the core of RL-NLS1s hampers the development of a high power jet. This question will likely be answered by the continuous monitoring that *Fermi*/LAT is performing on this and other sources of this type.

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473 JAVE), WIRO.

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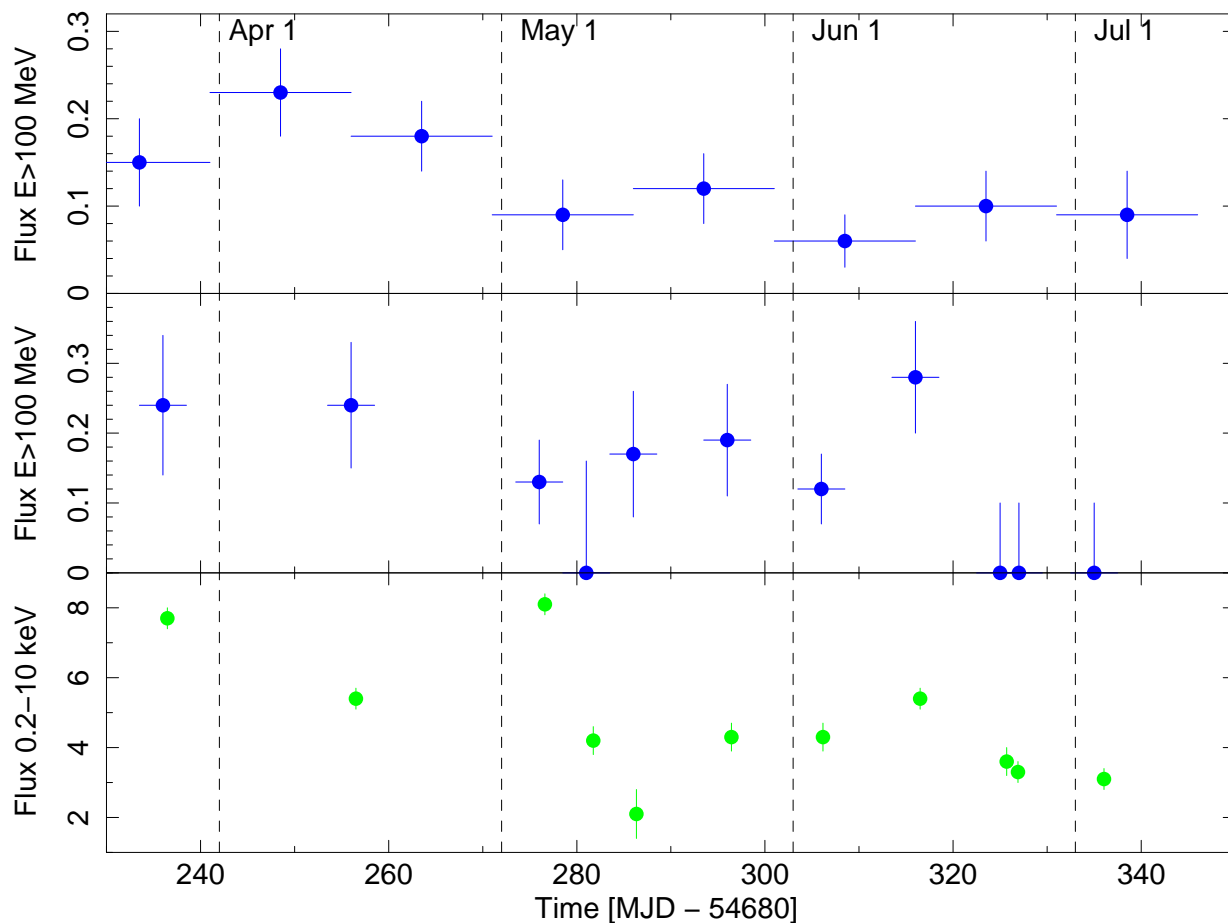


Fig. 1.— (*top panel*) γ -ray ($E > 100$ MeV) light curve from *Fermi*/LAT [10^{-6} ph cm $^{-2}$ s $^{-1}$], covering the whole period of the campaign. The bin time is 15 days. (*center panel*) γ -ray ($E > 100$ MeV) light curve from *Fermi*/LAT [10^{-6} ph cm $^{-2}$ s $^{-1}$], with 5 days bin time centered on *Swift* epochs. (*bottom panel*) X-ray (0.2 – 10 keV) light curves from *Swift*/XRT [10^{-12} erg cm $^{-2}$ s $^{-1}$].

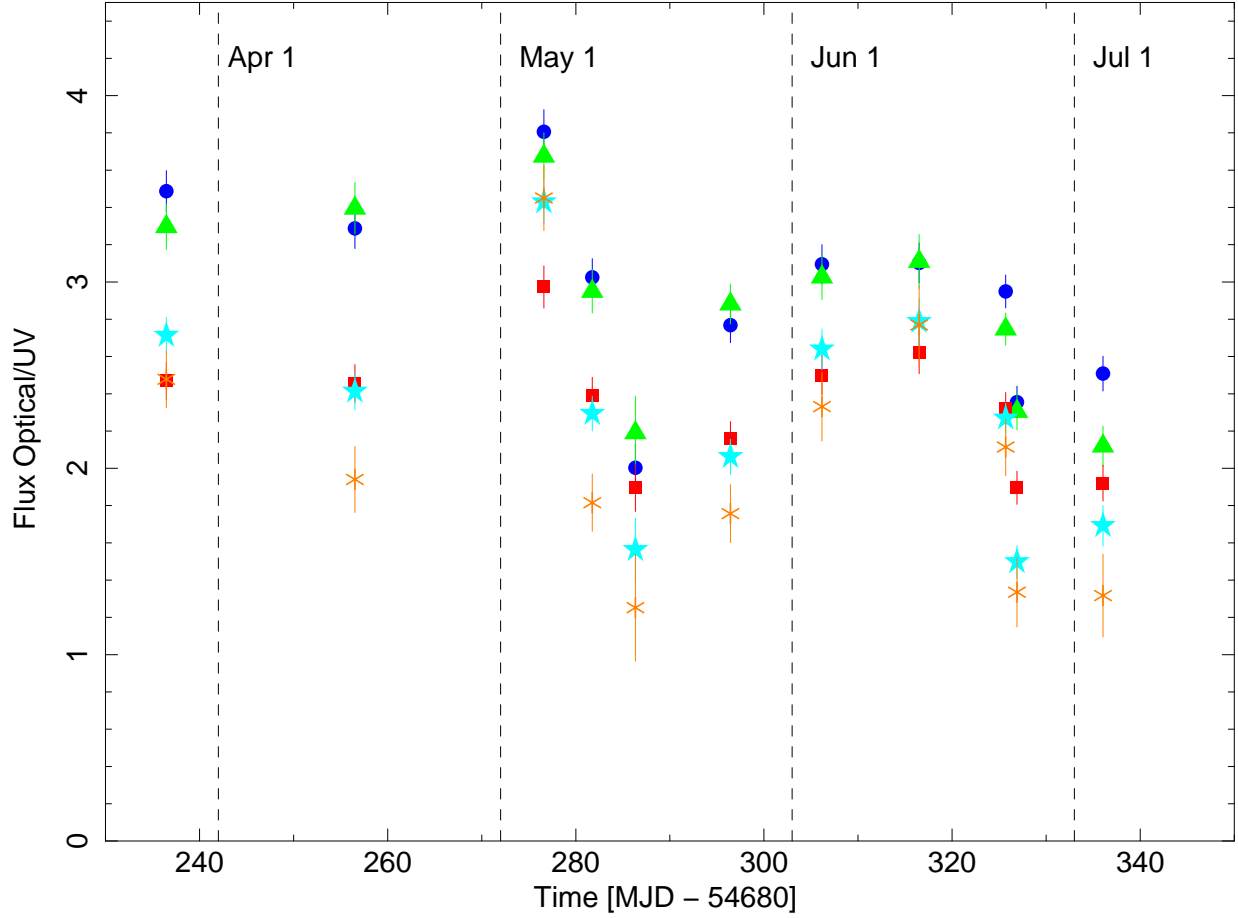


Fig. 2.— *Swift*/UVOT light curves of PMN J0948+0022 for the three ultraviolet filters (squares: UVW1; triangles: UVM2; circles: UVW2) and two optical filters (stars: U; asterisks: V). Fluxes (νF_ν) are in units of $10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$.

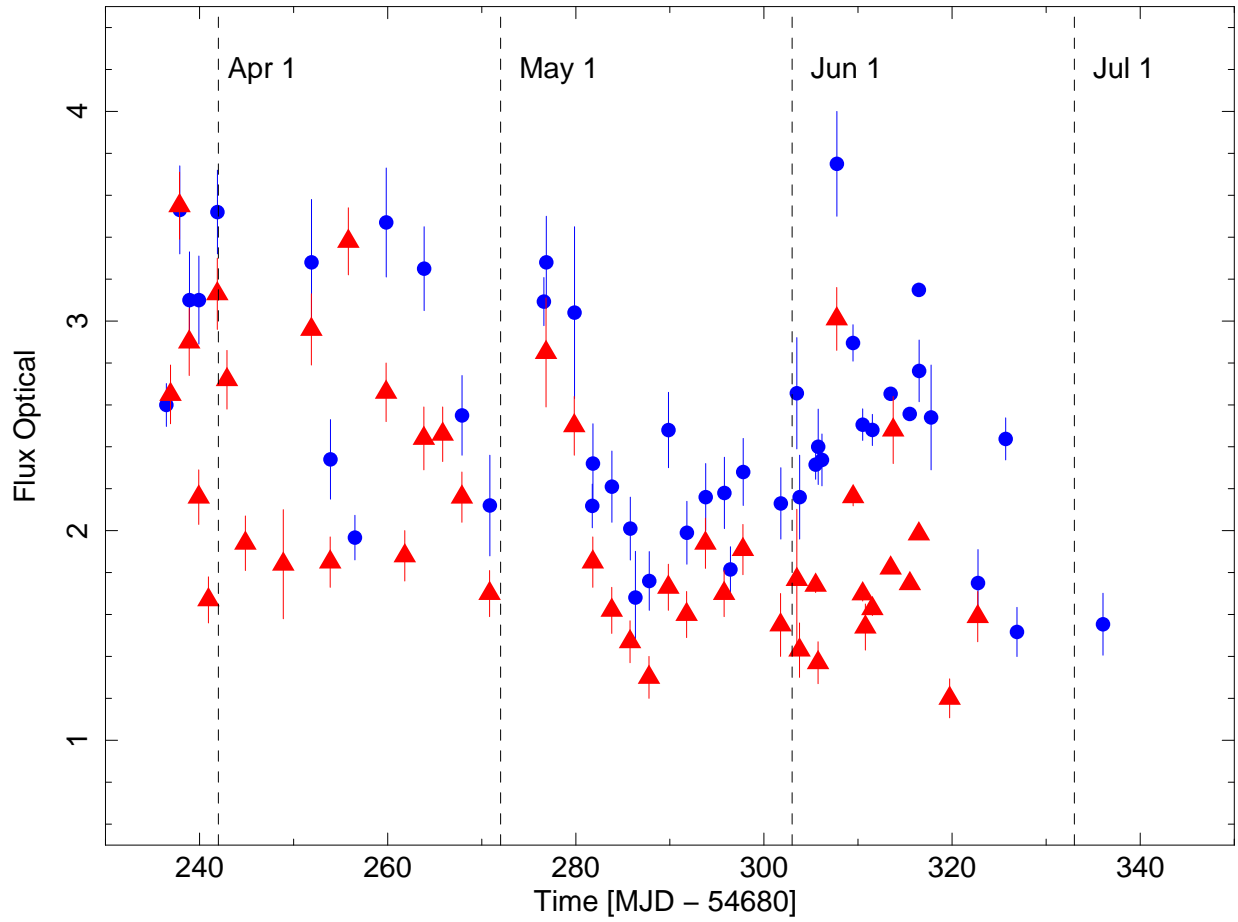


Fig. 3.— *Swift*/UVOT (B), ATOM (B, R) and SMARTS (B, R) optical light curves of PMN J0948+0022 (circles: B; triangles: R). Fluxes (νF_ν) are in units of 10^{-12} erg cm $^{-2}$ s $^{-1}$.

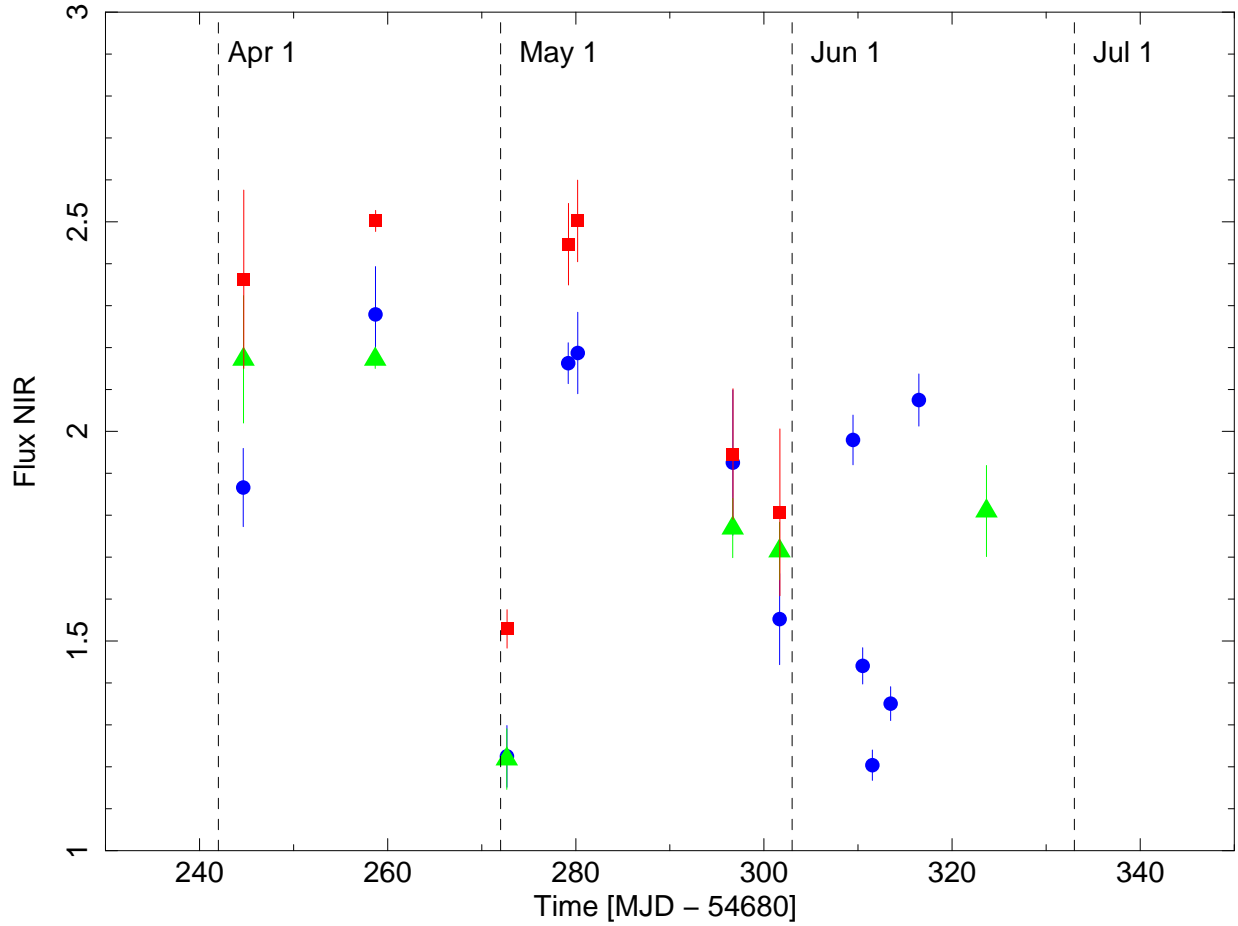


Fig. 4.— SMARTS (J), WIRO (J, K_s) and INAOE (J, H, K_s) near-infrared light curves of PMN J0948+0022 (circles: J; triangles: H; squares: K_s). Fluxes (νF_ν) are in units of 10^{-12} erg cm⁻² s⁻¹.

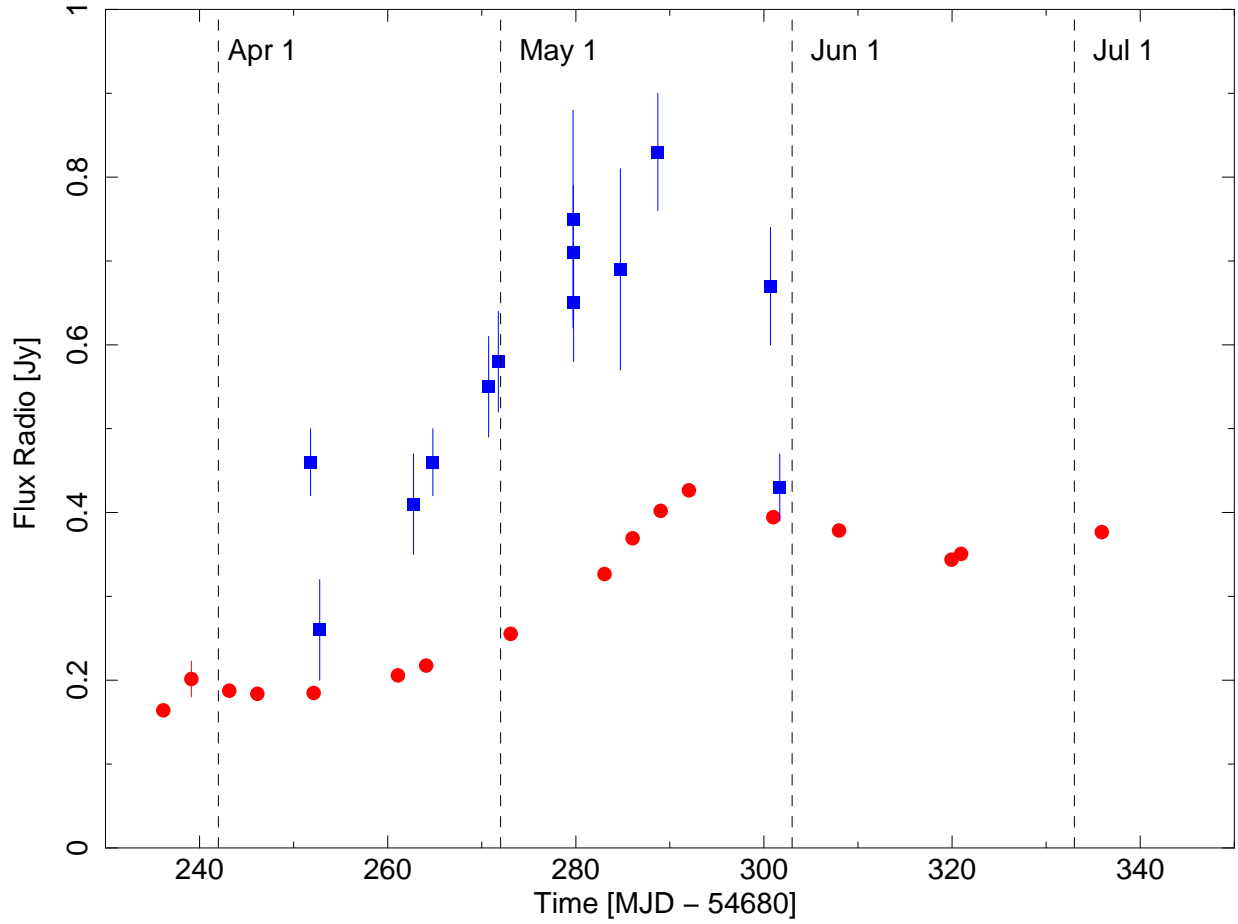


Fig. 5.— Radio light curves of PMN J0948+0022. Circles: 15 GHz data from OVRO; squares: 37 GHz data from Metsähovi.

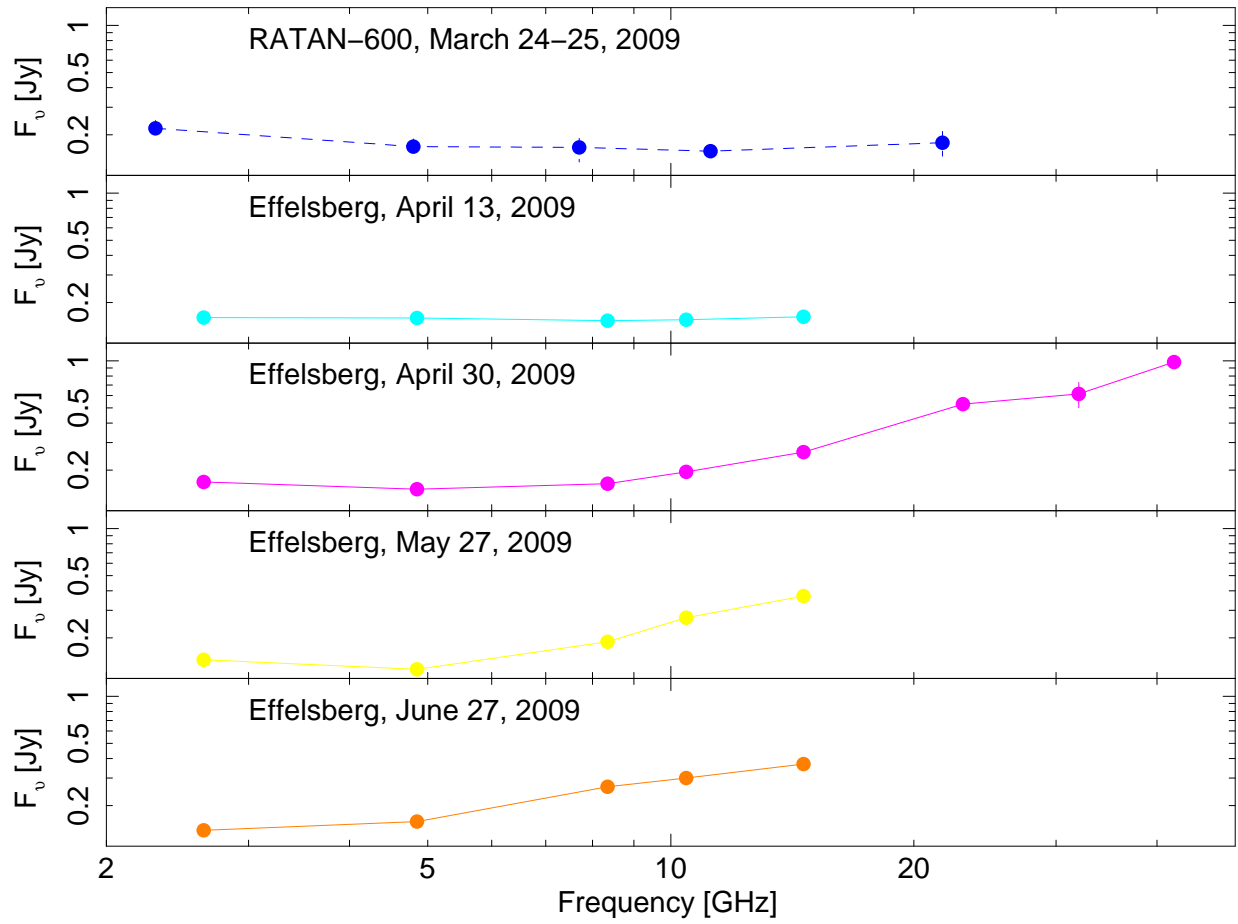


Fig. 6.— Evolution of the radio spectrum of PMN J0948+0022 as observed from Effelsberg and RATAN.

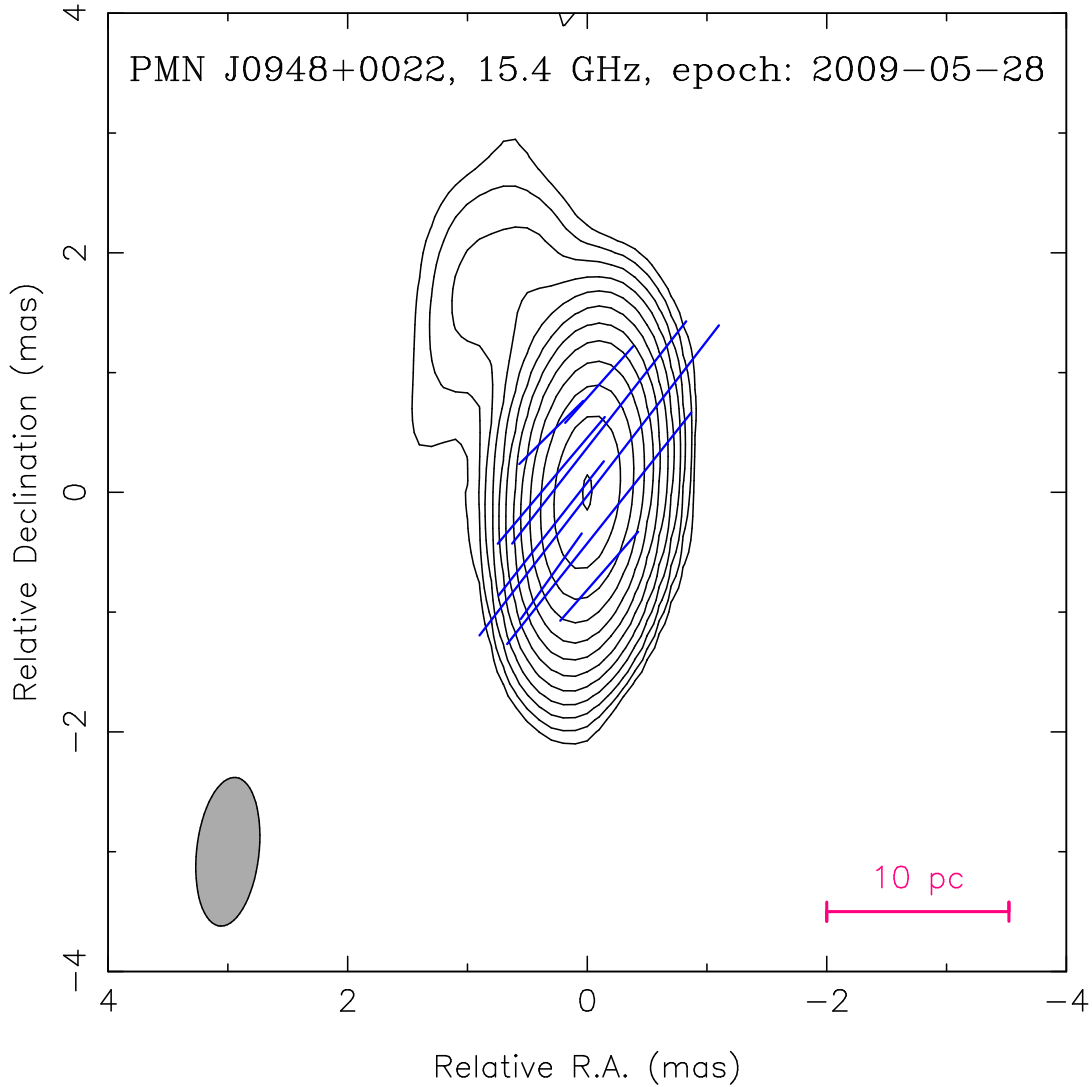


Fig. 7.— VLBA (MOJAVE program) 15 GHz combined total intensity and linear polarization image of PMN J0948+0022 observed on 2009 May 28. The total intensity is shown by contours of equal intensity (with $\times 2$ steps). The lowest contour is 0.2 mJy/beam and the peak intensity reaches the value of 425 mJy/beam. The direction of the electric vectors is superimposed and represented by blue solid lines, with their length proportional to the intensity of the linear polarization, which peaks at 3.6 mJy/beam. The FWHM size of the restoring beam is shown in the left bottom corner. The spatial scale is 6.59 pc/mas in the adopted cosmology.

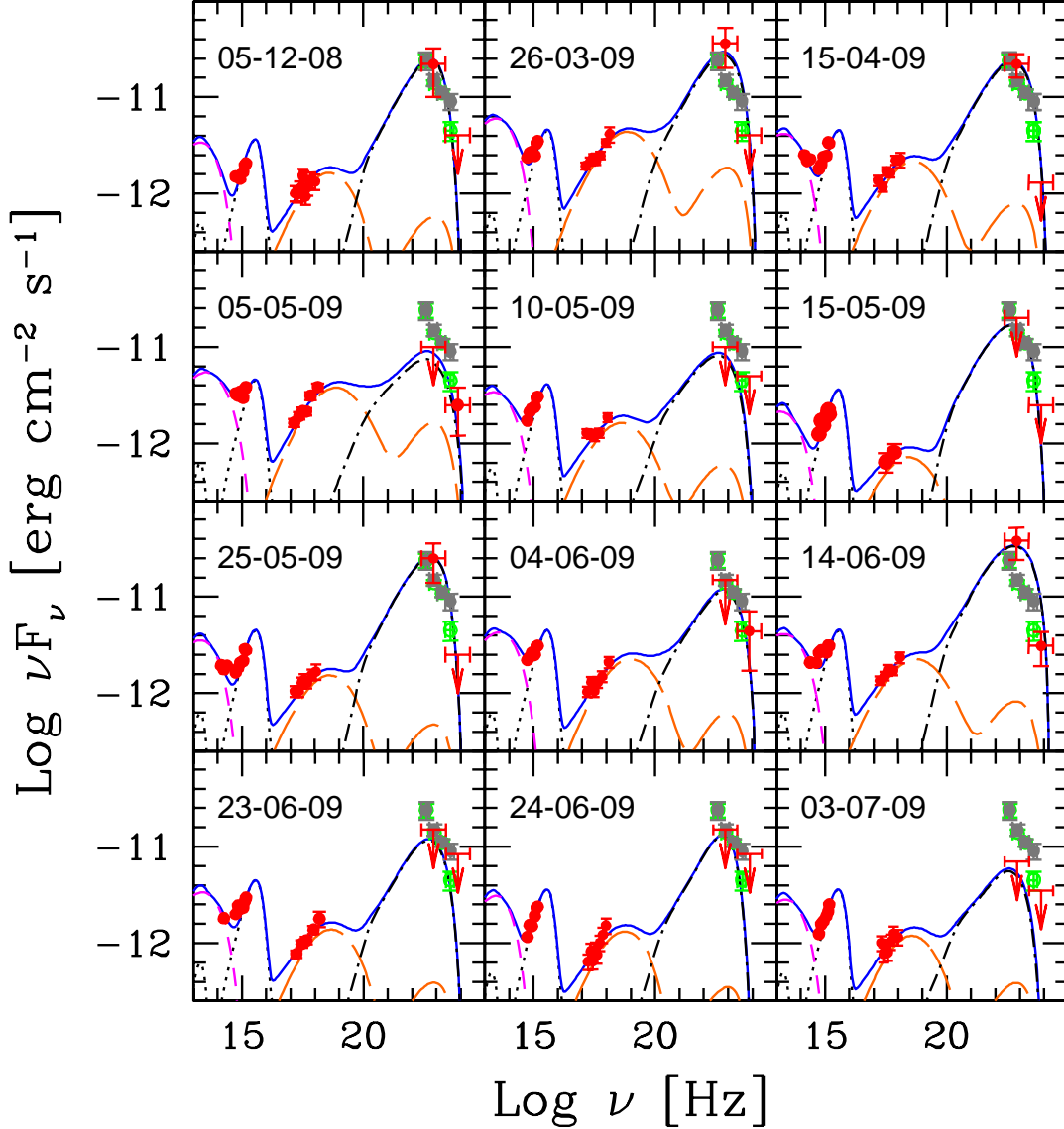


Fig. 8.— Individual SEDs built from the measurements obtained during the observations performed in the present multiwavelength campaign and centered on the *Swift* snapshots. The observation performed on December 5, 2008 is also shown (Abdo et al. 2009). Red points are the (quasi-)simultaneous data. The dotted line indicates the contribution from the accretion disk. The dashed line is the synchrotron self-Compton (SSC) and the dot-dashed line is the external Compton (EC). The blue continuous line is the sum of all the contributions. LAT spectra integrated over the three months of this campaign (grey points) and that integrated on August-December 2008 (green points) from Abdo et al. (2009) are also shown (these are almost consistent, except for the last bin at the highest energy).

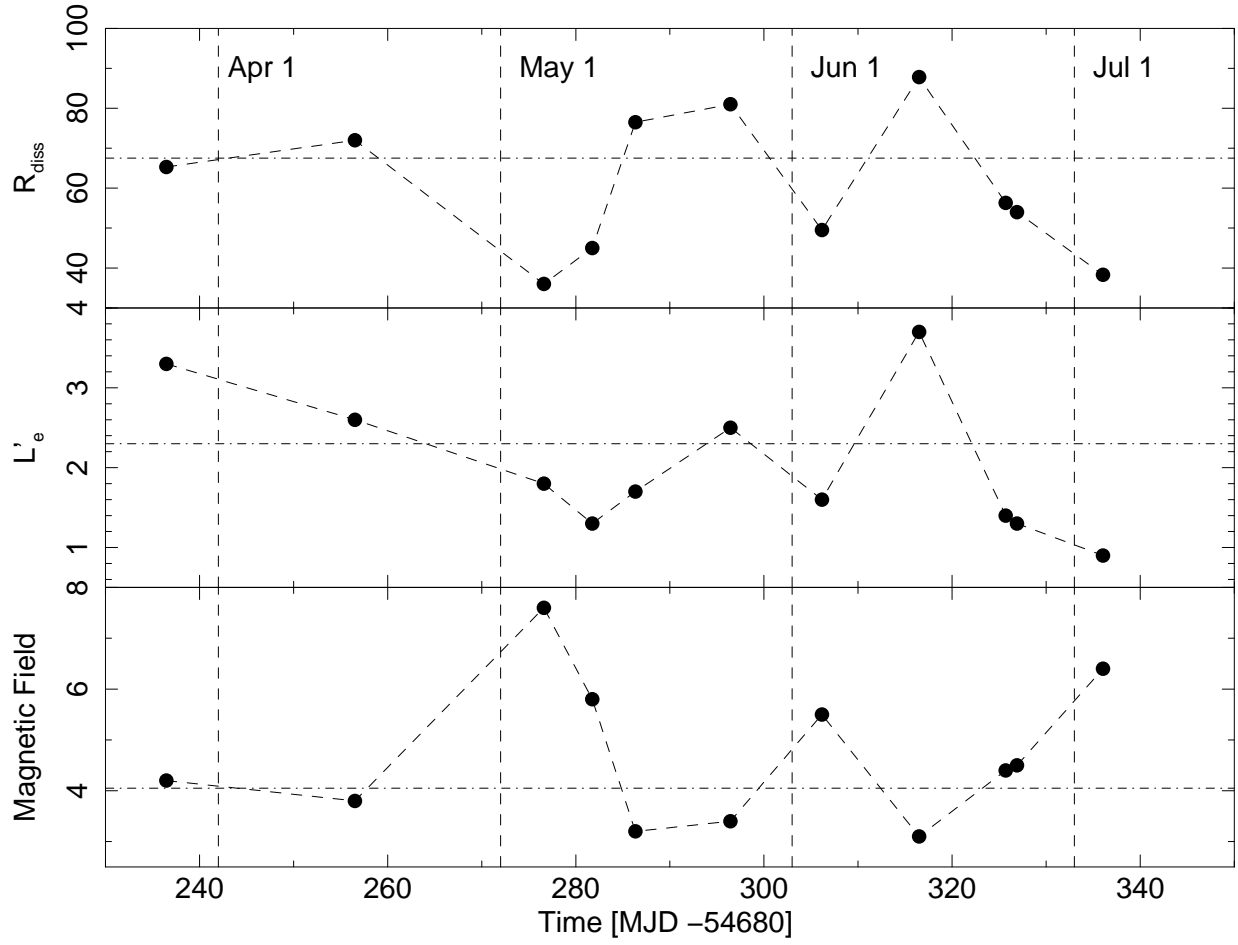


Fig. 9.— Evolution of models parameters derived from the fits of individual SEDs. R_{diss} is the dissipation radius in units of [10^{15} cm]; L'_e is the injected electron power in units of [10^{43} erg s $^{-1}$]; the magnetic field B is in units of [gauss]. The dot-dashed lines indicate the value obtained from the fit of the overall SED.

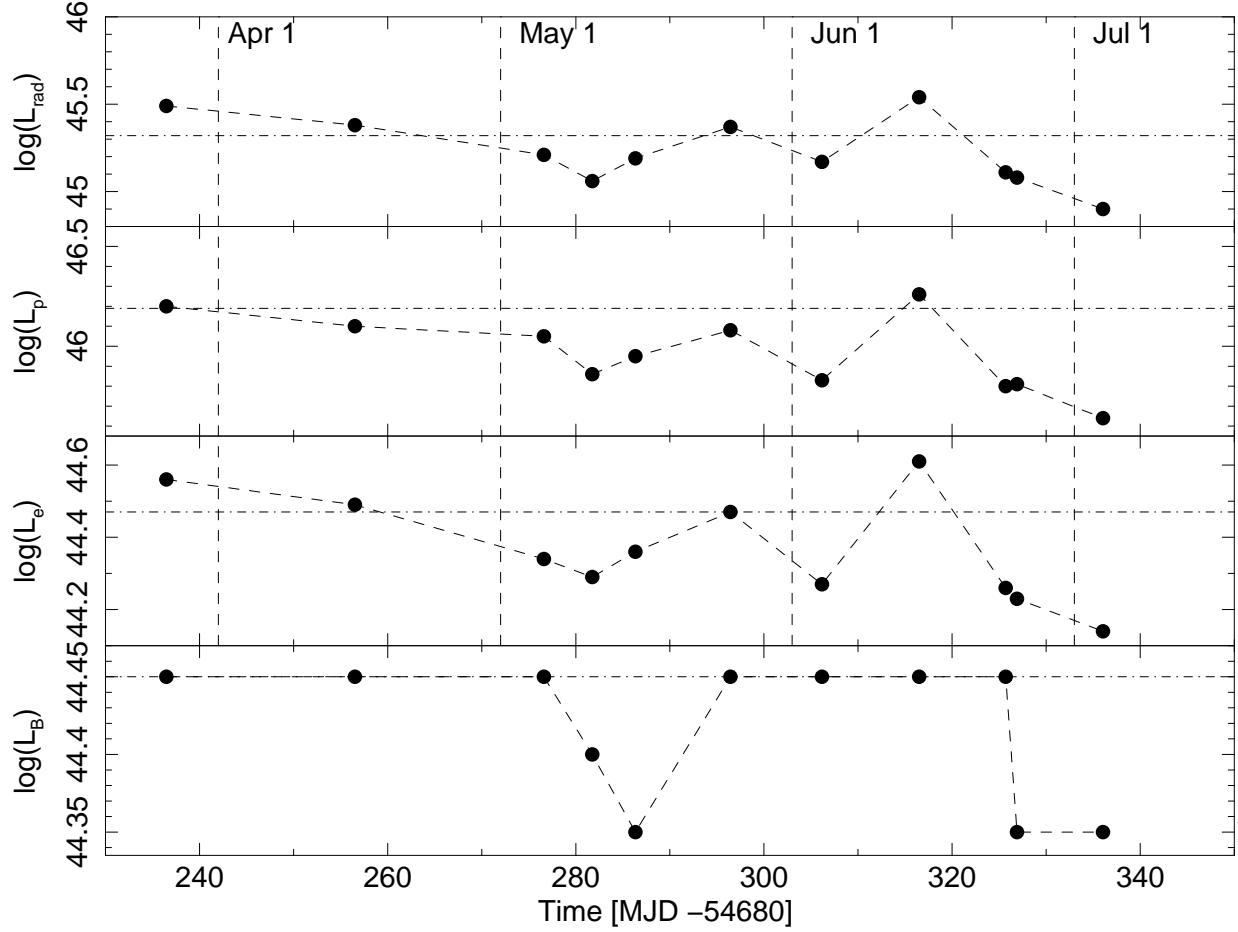


Fig. 10.— Evolution of models parameters derived from the fits of individual SEDs. From top to bottom: radiation, proton, electron and magnetic field powers in units of $[\text{erg s}^{-1}]$. The dot-dashed lines indicate the value obtained from the fit of the overall SED.

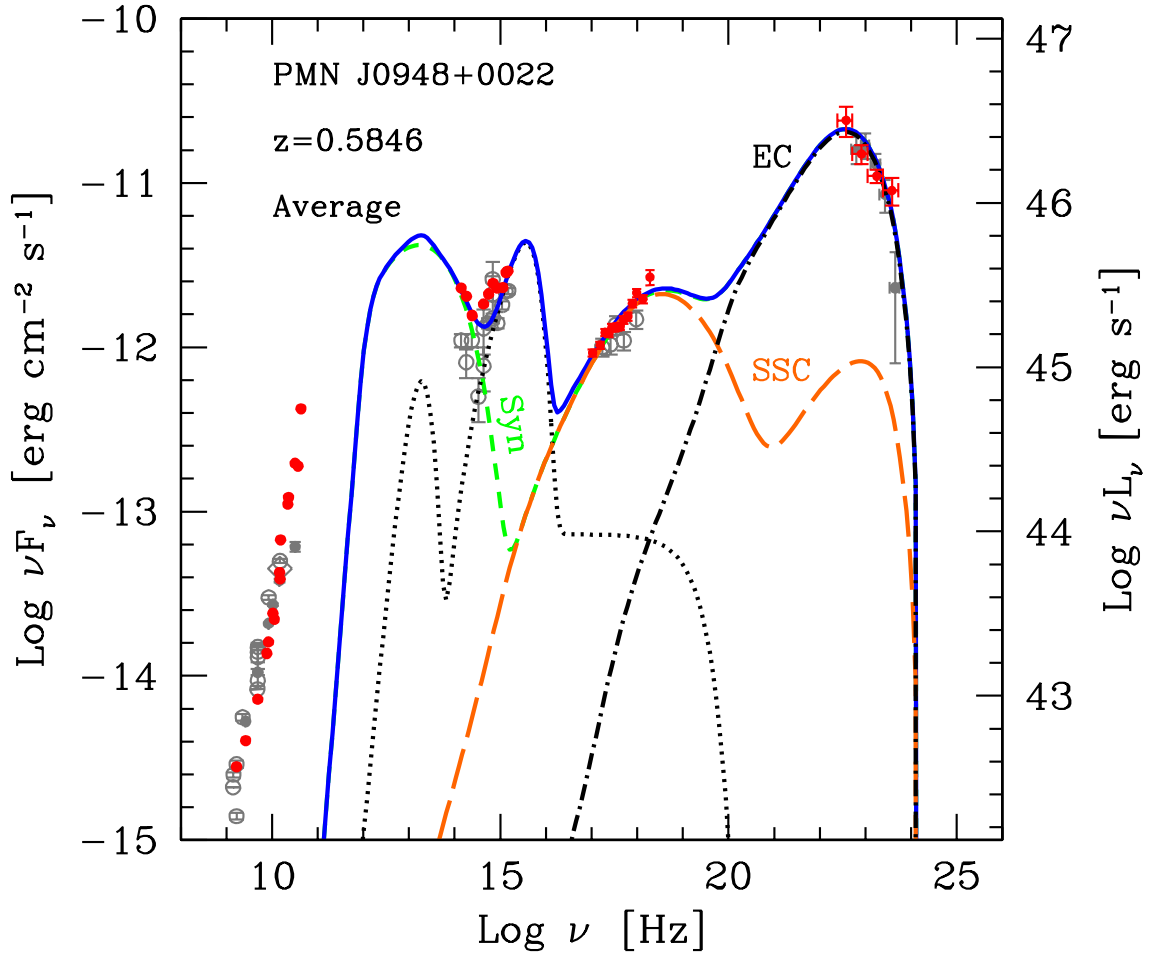


Fig. 11.— Overall SED built from all the measurements obtained during the observations performed in the present multiwavelength campaign. Red points are the data collected during the present campaign. The dotted black line indicates the contribution from the accretion disk, X-ray corona and IR torus. The short-dashed green line is the synchrotron (Syn) and the long-dashed orange line is the synchrotron self-Compton (SSC). The dot-dashed black line is the external Compton (EC). The blue continuous line is the sum of all the contributions. Grey symbols indicate archival data from Abdo et al. (2009). The fit does not include radio data, although they are displayed, since they are produced in regions external to that of the γ rays. The region of synchrotron self-absorption is clearly visible around 10^{11} Hz.

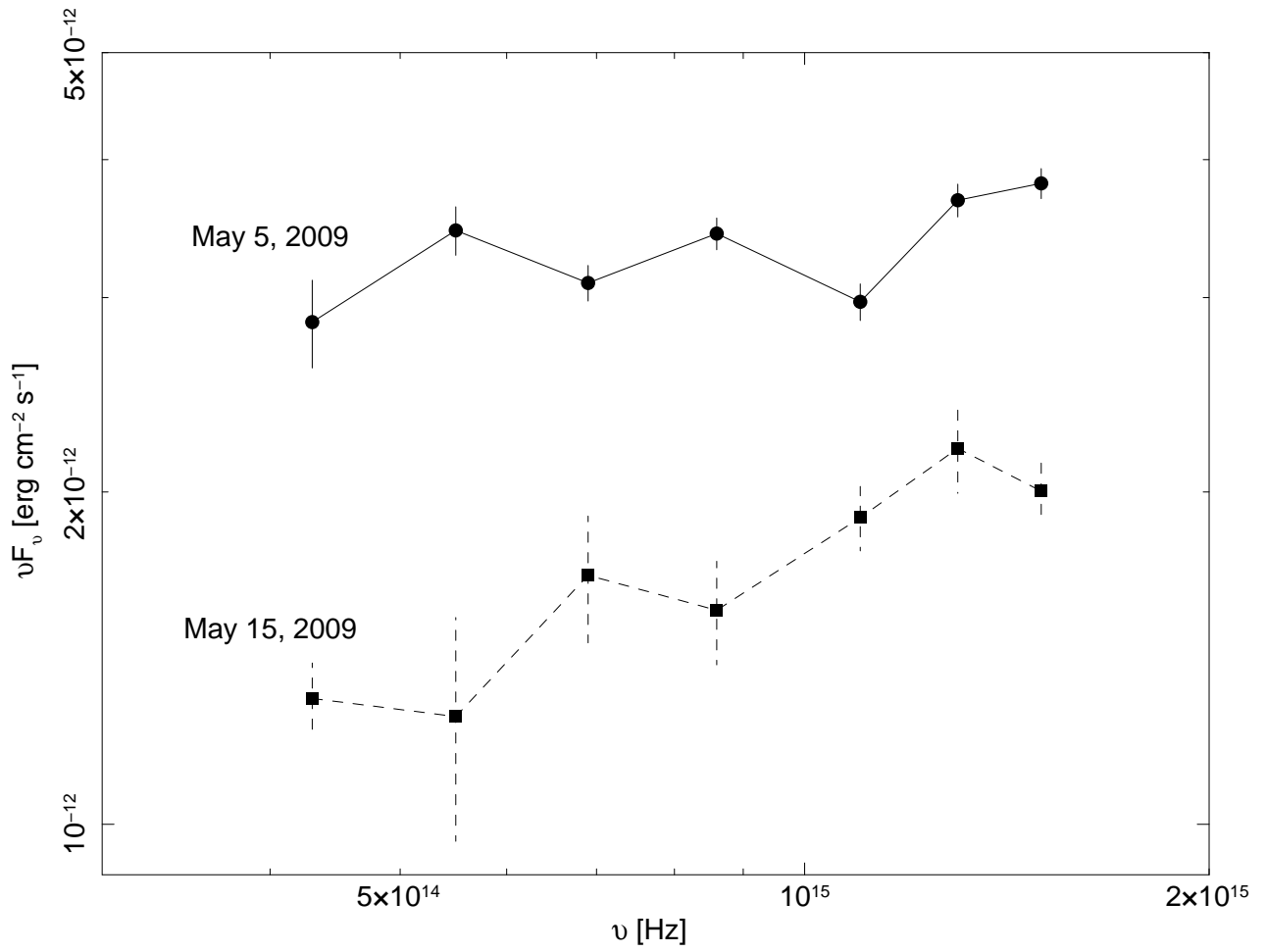


Fig. 12.— Zoom of the SED into the optical/UV frequencies of PMN J0948+0022, as observed on May 5 and 15.

Table 1: Summary of the spectral fitting of the *Fermi*/LAT data on a monthly timescale.

| Time Period | $F_{E>100\text{MeV}}$ [10^{-7} ph cm $^{-2}$ s $^{-1}$] | Γ | TS |
|--------------|--|---------------|-----|
| April 2009 | 2.2 ± 0.4 | 2.7 ± 0.2 | 158 |
| May 2009 | 1.2 ± 0.3 | 2.4 ± 0.2 | 65 |
| June 2009 | 1.0 ± 0.2 | 2.2 ± 0.2 | 76 |
| Aug-Dec 2008 | 1.6 ± 0.1 | 2.7 ± 0.1 | 386 |

Table 2: Summary of results from analysis of the *Swift*/XRT data. See the text for details and Fig. 1.

| ObsID | Time [MJD] | Exposure [ks] | Γ | Flux _{0.2–10keV} [10^{-12} erg cm $^{-2}$ s $^{-1}$] | χ^2/dof | Notes |
|-------------|---------------|------------------|-----------------|--|---------------------|--|
| 00031306002 | 54916.26 | 4.8 | 1.75 ± 0.10 | 7.7 ± 0.3 | 33.7/23 | |
| 00031306003 | 54936.34 | 4.4 | 1.67 ± 0.13 | 5.4 ± 0.3 | 14.4/13 | |
| 00031306004 | 54956.42 | 4.8 | 1.61 ± 0.09 | 8.1 ± 0.3 | 18.8/22 | |
| 00031306005 | 54961.51 | 4.9 | 1.83 ± 0.14 | 4.2 ± 0.4 | 5.7/12 | |
| 00031306006 | 54966.13 | 1.4 | 1.77 ± 0.49 | 2.1 ± 0.7 | – | 2 PHA bins; Cash statistic (Cash 1979) |
| 00031306007 | 54976.43 | 5.0 | 1.75 ± 0.14 | 4.3 ± 0.4 | 7.2/11 | |
| 00031306008 | 54986.16 | 4.5 | 1.72 ± 0.15 | 4.3 ± 0.4 | 9.1/10 | |
| 00031306009 | 54996.04 | 3.9 | 1.69 ± 0.14 | 5.4 ± 0.3 | 14.1/11 | |
| 00031306010 | 55005.42 | 7.7 | 1.63 ± 0.11 | 3.6 ± 0.4 | 7.5/15 | |
| 00031306011 | 55006.81 | 4.7 | 1.52 ± 0.23 | 3.3 ± 0.3 | 3.6/6 | |
| 00038394001 | 55015.53 | 4.2 | 1.77 ± 0.25 | 3.1 ± 0.3 | 3.3/5 | |

Table 3: Summary of the observed fluxes from e-VLBI. See the text for details.

| Time (MJD) | Frequency (GHz) | Flux density [Jy] | T_B [K] | Resolution [mas \times mas, deg] |
|---------------|--------------------|----------------------|------------------------|---------------------------------------|
| 54942 | 1.66 | 0.17 ± 0.03 | $> 1.7 \times 10^6$ | 35.4×22.9 , 12 |
| 54974 | 22.2 | 0.7 ± 0.2 | $> 3.1 \times 10^{10}$ | 0.22×0.59 , 24 |
| 54992 | 22.2 | 0.3 ± 0.1 | $> 2.3 \times 10^{10}$ | 0.19×0.47 , 28 |
| 55016 | 22.2 | 0.5 ± 0.1 | $> 1.5 \times 10^{10}$ | 0.41×0.48 , 55 |

Table 4. Summary of the fits of the SEDs.

| Time (1) | R_{diss} (2) | L_{disk} (3) | L'_{e} (4) | B (5) | $\gamma_{\text{e,break}}$ (6) | $\gamma_{\text{e,max}}$ (7) | $\gamma_{\text{e,peak}}$ (8) | s_1 (9) | s_2 (10) | U' (11) | $\log L_{\text{rad}}$ (12) | $\log L_{\text{p}}$ (13) | $\log L_{\text{e}}$ (14) | $\log L_{\text{B}}$ (15) |
|--------------------|--------------------------|--------------------------|------------------------|------------|----------------------------------|--------------------------------|---------------------------------|--------------|---------------|--------------|-------------------------------|-----------------------------|-----------------------------|-----------------------------|
| 54916 | 65.3 | 0.5 | 3.3 | 4.2 | 700 | 2000 | 675 | -0.5 | 2.2 | 4.4 | 45.49 | 46.20 | 44.56 | 44.45 |
| 54936 | 72.0 | 0.5 | 2.6 | 3.8 | 600 | 1900 | 556 | -0.25 | 2.2 | 3.9 | 45.38 | 46.10 | 44.49 | 44.45 |
| 54956 | 36.0 | 0.5 | 1.8 | 7.6 | 400 | 2200 | 462 | -1.0 | 2.2 | 8.1 | 45.21 | 46.05 | 44.34 | 44.45 |
| 54961 | 45.0 | 0.45 | 1.3 | 5.8 | 500 | 1800 | 476 | 0.0 | 2.2 | 5.3 | 45.06 | 45.86 | 44.29 | 44.40 |
| 54966 | 76.5 | 0.4 | 1.7 | 3.2 | 600 | 1800 | 526 | 0.0 | 2.2 | 3.4 | 45.19 | 45.95 | 44.36 | 44.35 |
| 54976 | 81.0 | 0.5 | 2.5 | 3.4 | 900 | 1700 | 636 | 0.0 | 2.2 | 3.6 | 45.37 | 46.08 | 44.47 | 44.45 |
| 54986 | 49.5 | 0.5 | 1.6 | 5.5 | 700 | 2100 | 656 | -0.5 | 2.2 | 5.1 | 45.17 | 45.83 | 44.27 | 44.45 |
| 54996 | 87.7 | 0.5 | 3.7 | 3.1 | 600 | 2500 | 604 | 0.0 | 2.2 | 3.6 | 45.54 | 46.26 | 44.61 | 44.45 |
| 55005 | 56.3 | 0.5 | 1.4 | 4.4 | 600 | 1700 | 543 | -0.5 | 2.2 | 4.4 | 45.11 | 45.80 | 44.26 | 44.45 |
| 55007 | 54.0 | 0.4 | 1.3 | 4.5 | 900 | 1400 | 640 | -1.0 | 2.2 | 4.3 | 45.08 | 45.81 | 44.23 | 44.35 |
| 55015 | 38.3 | 0.4 | 0.9 | 6.4 | 500 | 1500 | 465 | -0.5 | 2.2 | 5.8 | 44.90 | 45.64 | 44.14 | 44.35 |
| Overall | 67.5 | 0.5 | 2.3 | 4.1 | 530 | 2000 | 464 | -1.0 | 2.7 | 4.0 | 45.32 | 46.19 | 44.47 | 44.45 |
| 54805 | 72.0 | 0.4 | 2.3 | 3.4 | 1000 | 1500 | 623 | -0.25 | 2.2 | 3.7 | 45.33 | 46.04 | 44.45 | 44.35 |
| Abdo et al. (2009) | 67.5 | 0.4 | 3.2 | 2.4 | 800 | 1600 | 411 | 1.0 | 2.2 | 3.7 | 45.30 | 46.68 | 44.70 | 44.25 |

Note. — Columns: (1) time [MJD]; (2) radius at which most of the dissipation occurs [10^{15} cm]; (3) luminosity of the accretion disk in Eddington units; (4) injected electron power in the comoving frame [10^{43} erg s $^{-1}$]; (5) magnetic field [gauss]; (6, 7, 8) random electron Lorentz factors $\gamma_{\text{e,break}}$, $\gamma_{\text{e,max}}$ and $\gamma_{\text{e,peak}}$, respectively; (9, 10) power law indexes of the electron distribution below and above $\gamma_{\text{e,break}}$, respectively; (11) radiation and magnetic energy density in the comoving frame [erg cm $^{-3}$]; (12, 13, 14, 15) radiation, proton, electron and magnetic field power of the jet [erg s $^{-1}$]. See the text for details and Fig. 11.

Table 5: Results of the fitting of the light curves with a constant flux line and maximum observed factor of flux change.

| Band/Filter/Frequency | $\tilde{\chi}^2$ | Factor Flux Change |
|-----------------------|------------------|--------------------|
| γ ray | 2.0 | 2.2 |
| X-ray | 30.3 | 3.9 |
| UVW2 | 22.0 | 1.9 |
| UVM2 | 16.7 | 1.9 |
| UVW1 | 10.2 | 1.8 |
| U | 28.3 | 2.4 |
| B | 19.6 | 2.5 |
| V | 12.5 | 2.7 |
| R | 22.4 | 2.9 |
| J | 46.8 | 1.9 |
| H | 41.6 | 1.8 |
| K | 60.9 | 1.6 |
| 37 GHz | 5.9 | 3.2 |
| 15 GHz | 252.3 | 2.6 |