The Optical Properties of PKS 1222+216 During the Fermi Mission

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The optical properties of the $z = 0.435$ quasar PKS 1222+216 (4C+21.35) are summarized since the discovery of impressive $\gamma$-ray activity in this source by Fermi/LAT. Unlike several other $\gamma$-ray-bright blazars, there appears to be little connection between optical and $\gamma$-ray activity. Spectropolarimetry shows this object to be a composite system with optical emission from both a polarized, variable synchrotron power-law and unpolarized light from a stable blue continuum source (+broad emission-line region) contributing to the observed spectrum. Spectrophotometry over a period of about two years does not detect significant variability in the strong, broad emission lines, despite large optical continuum variations. This suggests that the relativistic jet has little influence on the output of the broad emission-line region, possibly either because the highly beamed continuum ionizes only a small portion of the line-emitting gas, or the observed non-thermal continuum originates parsecs downstream from the base of the jet, further away from the central engine than the broad emission-line region.

I. INTRODUCTION AND OBSERVATIONS

Since the announcement on 2009 April 17 [1] that the Large Area Telescope (LAT) aboard the Fermi Gamma-ray Space Telescope [2] detected increased $\gamma$-ray emission from PKS 1222+216, we have been systematically monitoring this $z = 0.435$ blazar at optical wavelengths. PKS 1222+216 is now among the two dozen or so $\gamma$-ray-bright blazars that form the core of the sample being monitored by Steward Observatory [3] in support of Fermi. This optical program uses the 2.3 m Bok and 1.54 m Kuiper telescopes with the SPOL spectropolarimeter [4] and provides publicly available spectropolarimetry, spectrophotometry, and calibrated broadband flux measurements for about 40 blazars [5]. PKS 1222+216 provides an example of how these data can be used to construct a comprehensive view of the optical behavior of blazars that can then be compared to observations made by the LAT and at other wavelengths.

In both the $\gamma$-ray and optical spectral regimes, the variability of PKS 1222+216 is characterized by numerous short-duration flares. For instance, the 0.1-300 GeV light curve shows at least 8 outbursts, each lasting just a few days at most (Figure 1). Similarly, large daily fluctuations in both the optical flux and polarization are observed over the ~2-year period. Interestingly, the optical and $\gamma$-ray activity do not show a direct correspondence, unlike several other well-studied blazars where the site(s) of $\gamma$-ray production can be directly tied to those producing the bulk of the optical and radio flux [6, 7]. In particular, a recent optical outburst of PKS 1222+216 in 2011 March occurred without any apparent corresponding $\gamma$-ray activity.

Figure 2 summarizes the nearly simultaneous (within 12 hr) LAT $\gamma$-ray and optical measurements from Steward Observatory of PKS 1222+216. The $\gamma$-ray flux is not found to be correlated with the V-band optical brightness, the degree of optical polarization of the synchrotron continuum ($P_0$; see §3), or the polarization position angle, $\theta$. Although nearly the entire range of $\theta$ is observed during monitoring program, the majority of the optical measurements show $\theta$ to be within 30° of north, more-or-less aligned with both the position angles of the VLBI jet [8, 9] and the polarized flux of the millimeter core [4].

II. EMISSION LINES

The optical spectrum of the object exhibits strong, broad MgII and Balmer emission lines. Narrow-line emission in PKS 1222+216 is weak, although [O III]λ5007 is detected in the moderate-resolution spectra obtained by SPOL. Because the Steward Observatory program provides calibrated spectrophotometry in addition to linear polarization data, the flux spectrum of PKS 1222+216 is monitored routinely. The emission from the broad-line region does not vary on the extremely short time scales observed for the continuum. Indeed, measurements of the Hβ and Hγ fluxes over the two-year period do not detect significant changes in the emission-line flux (Figure 3, right panel). The constancy of the line fluxes is also reflected in the left panel of Figure 3, as the equivalent widths (EWs) of both Hβ and Hγ systematically decrease as the optical continuum brightens. The larger
FIG. 1: Top panel: The $\gamma$-ray (blue) and optical (red; from 2009 April 27–2011 March 8) flux variations of PKS 1222+216. Weekly LAT averages are shown for the $\gamma$-ray light curve. Bottom panel: Optical polarization variations, with the degree of polarization, $P$, shown in red and the polarization position angle, $\theta$, in green. The dotted vertical lines denote the occurrence of eight distinct $\gamma$-ray outbursts. The major optical outburst during 2011 March (MJD $\sim$ 55625) has no apparent $\gamma$-ray analog.

scatter in the measurements for H$\beta$ compared to those for H$\gamma$ are due to the presence of the strong atmospheric O$_2$ absorption feature in the blue wing of H$\beta$ and fringing of the thinned CCD at these wavelengths.

The stability seen in the emission lines is consistent with the broad-line region of the blazar not being affected by the highly beamed and variable continuum produced by the jet. The lack of a coupling between the jet and the broad emission-line region may be the result of the beamed continuum intersecting only a small fraction of the volume containing the emission-line gas. The observed jet emission could also originate further away from the central engine than the extent of the region containing the broad-line emitting clouds, which is measured to be a few to several light months from the ionizing continuum source (see, e.g., [10]). The latter possibility is in line with other evidence that suggests that the non-thermal continuum originates several parsecs from the base of the relativistic jet [6, 7, 11].

III. OPTICAL CONTINUUM AND POLARIZATION

Although few connections can be found between the optical and $\gamma$-ray variability in PKS 1222+216, strong correlations are found optically between flux, color, and polarization (Figure 4). As PKS 1222+216 brightens, the continuum becomes redder. In addition, the polarization is almost always observed to decrease toward the blue regardless of the level of polarization observed ($P_{\text{obs}} < 10\%$). The decrease in $P$ to the blue is also generally found to be stronger when the blazar is faint (middle panel of Figure 4). Similarly, the polarization is observed to decrease in the major broad emission lines. This is especially apparent for the high-EW H$\beta$ line, and is consistent with the emission-line flux being completely unpolarized. In contrast to $P$, the polarization position angle generally remains constant across the spectrum. These trends are well illustrated in the individual observations of PKS 1222+216 shown in Figure 5.

The polarization properties and the correlation between brightness and optical color lead directly to a picture that has the optical emission coming from two sources: (1) a variable, polarized synchrotron continuum that is produced by the relativistic jet, and (2) a much more stable (at least on the time scale of a year or more), unpolarized source with a spectrum similar to an optically-selected QSO. Figure 6 shows an illustrative example of how such a simple two-component system explains all of the major optical correlations seen in PKS 1222+216 during the monitoring program. In this model, the synchrotron continuum is well described by a simple power law having constant polarization over the observed spectral range. Fitting the wavelength dependence observed in $P$ is accomplished by assuming that the flux additional to the synchrotron continuum is unpolarized. The resulting flux spectrum that explains the variation in polarization as a function of wavelength is quite similar to a typical optically-selected QSO in continuum color and broad-line emission. Similar models have been very successful in explaining the optical properties of several other highly polarized quasars (see [12], and references therein).

The particular model for PKS 1222+216 on 2011 March 8 (Figure 6) reveals that the intrinsic polarization ($P_0$) of the power-law component is independent of wavelength at nearly 15% and that its spectral index is $\alpha \sim -1.3$. Furthermore, the correlations between brightness, color, and polarization are reproduced by the model if the QSO component (essentially, a “Big Blue Bump” continuum that likely provides the ultraviolet flux that ionizes the broad emission-line region) is kept constant. The flux-color correlation (see Figure 4) arises because as the variable jet emission brightens, its relatively redder continuum becomes more dominant and reddens the overall spectrum. The models and observed correlations suggest an unpolarized component with an apparent V magnitude $\sim$16.2 (right panel of Figure 4). In turn, the observed polarizations can be corrected by subtracting the unpolarized light from the total flux.
FIG. 2: Simultaneous $\gamma$-ray and optical measurements. No clear trend is observed between $\gamma$-ray flux and either optical flux, polarization (corrected for unpolarized emission; see §3), or the polarization position angle, $\theta$. Upper limits for single-day LAT fluxes are shown as red triangles.

FIG. 3: Measurements of the equivalent width (EW) and flux of the H$\beta$ and H$\gamma$ emission lines. The line fluxes stay relatively constant with time and continuum brightness over the $\sim$2-yr period. As a result, the EWs are closely tied to variations of the optical continuum.

yielding an estimate of the intrinsic polarization of the synchrotron continuum. The corrected polarizations are shown in the middle panel of Figure 2 and can be substantial. The maximum observed polarization during period monitored is shy of 10%, but $P_0$ can reach $\sim$20%, putting PKS 1222+216 on par with other blazars. Of course, the dilution of the nonthermal polarization by the QSO component has no effect on $\theta$.

IV. SUMMARY AND CONCLUSIONS

PKS 1222+216 is an important object for continued intensive study across the entire electromagnetic spectrum. Although direct connections can be made between the optical and radio emission owing to the rough alignment of the polarizations and the position angle of the inner VLBI jet, there are significant differences between the behavior of this quasar relative to other $\gamma$-ray-bright blazars at optical and GeV energies. In particular, major optical or $\gamma$-ray events can occur with no obvious corresponding activity in the other energy regime. The importance of PKS 1222+216 to the questions of the how and where high-energy photons are produced in blazars is underlined by the recent discovery of TeV emission from this source [13]. Continued optical spectropolarimetry enables not only efficient monitoring of the high-energy tail of the primary relativistic electrons and the magnetic field within the jet, but also the “normal QSO” emission, which provides valuable information on the accretion processes that presumably give rise to the jet.

Acknowledgments

Monitoring of PKS 1222+216 and $\sim$40 other $\gamma$-ray-bright blazars at Steward Observatory has been made possible by NASA Fermi Guest Investigator grants NNX08AV65G and NNX09AU10G.

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FIG. 4: Left panel: The flux density ratio between 4700 Å and 6600 Å plotted against the V-band brightness. The object becomes redder as it brightens. Center panel: The same quantity plotted against the ratio of polarization at the same wavelengths. As the object fades, the polarization decreases more strongly to the blue. Right panel: The correction to the observed broad-band polarization as a function of apparent magnitude, assuming a constant source of light that dilutes the polarized flux ($P_0 \times F_\nu$) from a power-law continuum.

FIG. 5: Spectropolarimetry in the observed reference frame when the blazar is bright (red) and faint (blue). Top panel: The spectrum with major emission lines identified. The atmospheric O$_2$ feature in the blue wing of H$\beta$ is also marked. Middle panel: The q Stokes parameter rotated so that u averages to 0 over the spectrum. There is a distinct decrease in polarization to the blue when the object is either bright or faint. Bottom panel: The spectrum of $\theta$, which is generally observed to be constant with wavelength, as expected if the polarized emission is dominated by a single non-thermal source.

FIG. 6: PKS 1222+216 on 2011 March 8. Top panel: The optical spectrum is modeled with a polarized ($P_0 = 14.8\%$), power-law synchrotron source and an unpolarized, continuum+broad emission-line spectrum similar to a typical optically-selected QSO. Bottom panel: The effect of the dilution of the non-thermal polarized flux by the bluer QSO component. The model is shown by the blue curve and the observed data indicated in red. Such a picture explains both the decrease in $P$ toward shorter wavelengths and the observed correlation between optical color and flux.

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