Why Galaxies Care About AGB Stars:
A Continuing Challenge through Cosmic Time
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Comprehensive Panchromatic Data Analyses and Photoionization Modeling of NGC 6781

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Abstract. We characterized the dusty circumstellar nebula and central star of the C-rich bipolar planetary nebula (PN) NGC 6781 using our own Herschel data augmented with the archival data from UV to radio and constructed one of the most comprehensive photoionization PN models ever produced consisting of the ionized, atomic and molecular gas components as well as the dust component. We reproduced the observed spectral energy distribution (SED), constrained by 136 observational data points. The total nebula mass was estimated to be 0.41 $M_{\odot}$, with a significant fraction (about 70 %) of it existing in the photo-dissociation region (PDR) surrounding the ionized nebula. This finding demonstrates the critical importance of the PDR in PNe, which are typically recognized as the hallmark of ionized/H^+ region. It is therefore essential to characterize the PDR of the circumstellar nebula to understand material recycling in the Milky Way and other galaxies.

Keywords. planetary nebulae: individual (NGC 6781), circumstellar matter, stars: mass loss, stars: abundances

1. Plasma Diagnostics and Ionic/Elemental Abundance Analyses

We performed a comprehensive analysis of the panchromatic data obtained from the PN NGC 6781, spanning from UV to radio (consisting of photometric and spectroscopic data from a dozen facilities; Table 1 of Otsuka *et al.* 2017) to investigate the evolutionary status of the central star and the physical conditions of each of the ionized, atomic, and molecular gas components as well as the dust component in the nebula.

First, we carried out detailed plasma diagnostics to determine the spatially-resolved electron density and temperature along the radial direction in the equatorial plane of this nearly pole-on bipolar nebula. We found the following three distinct spatial regions at least: the ionized nebula ($n_{\rm H} = 300\,{\rm cm}^{-3}$, $T_{\rm e} = 24$ to 10 kK), the high density pile-up wall, which delineates the characteristic "ring" structure of the nebula ($n_{\rm H} = 960\,{\rm cm}^{-3}$, $T_{\rm e} = 10$ to 3 kK), and the even higher density PDR around the "ring" structure ($n_{\rm H} = 10^4\,{\rm cm}^{-3}$, $T_{\rm e} = 3$ to 1 kK).

We then derived elemental abundances in the nebula for the following nine species: He, C, N, O, Ne, Si, S, Cl, and Ar. By comparing the derived abundances with the abundance pattern of AGB nucleosynthesis models of Karakas (2010), we determined that the progenitor star of NGC 6781 was of $2.25 - 3.0\,M_{\odot}$ initially. We also derived the distance of 0.46 kpc by fitting the stellar luminosity as a function of the distance and effective temperature of the central star constrained by the adopted post-AGB evolutionary tracks. The detailed account of these comprehensive analyses are fully documented in our recent publication (Otsuka *et al.* 2017).

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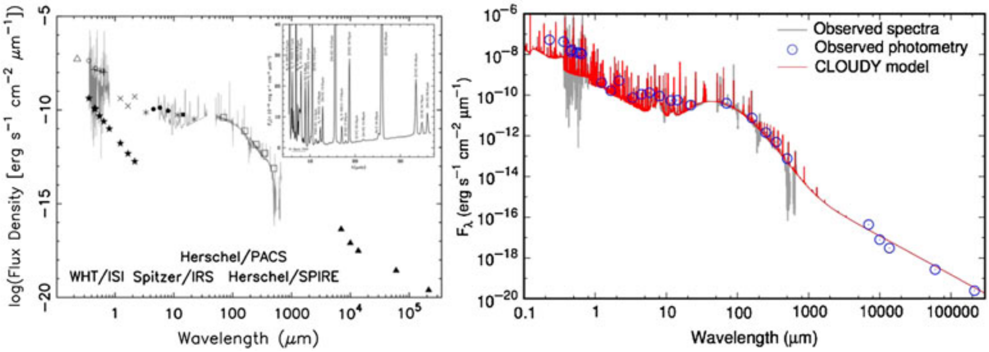

Figure 1. **[Left]** The panchromatic data of NGC 6781 adopted in the present study. Broadband photometry: GALEX (open triangle), ING/INT (open circles), ESO/NTT (pluses), UKIRT (crosses), WISE (asterisks), Spitzer (filled circles), ISO (filled square), Herschel (open squares), Radio (filled triangles), and HST/WFPC2 (filled stars for the central star). Spectra (grey lines): WHT/ISIS, Spitzer/IRS, and Herschel/PACS and SPIRE as indicated. The inset displays the Spitzer/IRS spectra in the mid-IR. **[Right]** The SED of the best-fit Cloudy model of NGC 6781 (red line; spectral resolution $R = 300$), compared with the observational constraints: photometry data (blue circles) and spectroscopy data (grey line). For full details, refer to Otsuka *et al.* (2017).

2. Dusty Photoionization Modeling with Cloudy

Next, by adopting the results of the above analyses as input parameters and model constraints, we constructed the best-fit photoionization model using Cloudy (Ferland *et al.* 2013). The total gas mass was found to be $0.41\,M_\odot$, with only $0.09\,M_\odot$ ionized, $0.20\,M_\odot$ atomic, and $0.11\,M_\odot$ molecular gases. The total dust mass was found to be $1.53 \times 10^{-3}\,M_\odot$, which would make the gas-to-dust mass ratio to be 268. Hence, the total nebula mass accounted for purely from the available data turned out to be roughly 60 % of the amount of mass predicted to have been ejected during the last thermal pulse episode from a star of $2.5\,M_\odot$ initial mass (Karakas 2010). The fact that the ionized gas was found to be only about 20 % of the total mass in a PN emphasizes that the colder dusty PDR that surrounds the ionized nebula carries greater significance in terms of the progenitor's mass-loss history and cannot be neglected to account for the full energetics of the nebula, even though PNe are generally known as ionized gas and H^+ regions.

The present work demonstrated that PNe could indeed serve as (1) empirical constraints for stellar evolutionary models, because empirically derived central star and nebula parameters could now confront theoretical predictions (and the present AGB models are shown to be consistent), and (2) important probes of mass recycling and chemical evolution in galaxies because PNe would permit thorough mass accounting of the mass-loss ejecta in the circumstellar environments.

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