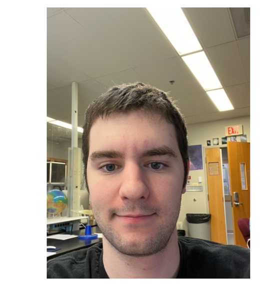
Towards a Better Understanding of the Relationship Between Black Hole Accretion and Maser Emission Via Mid-Infrared Variability and Structure Function



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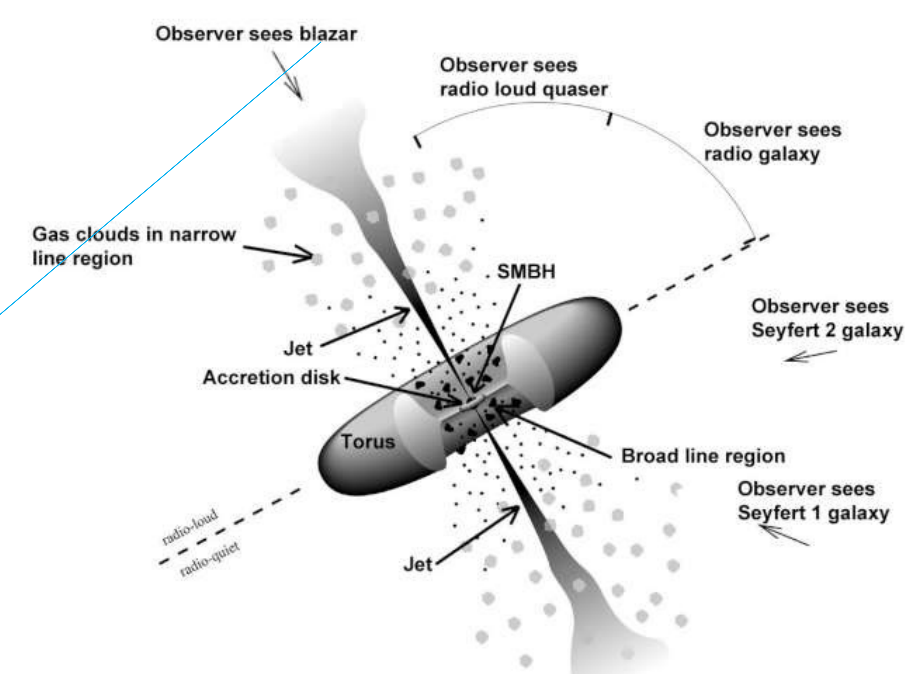
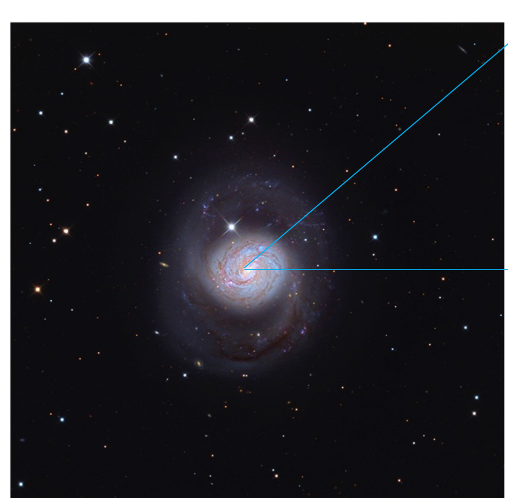
Abstract

Accretion of matter onto supermassive black holes ubiquitously found in galaxy centers, called Active Galactic Nuclei (AGN), is an important way of identifying hidden matter in the universe. A very small fraction of galaxy centers also exhibits Microwave Amplification by Stimulated Emission of Radiation (Maser), which, when in a disc-like configuration provides a direct way of measuring two main things: 1) the mass of the black hole and 2) distances to other galaxies via a geometric method, which does not involve standard candles. Therefore, it is very important to increase the detection rates of maser discs. We can do this by better understanding the physical conditions that lead to maser emissions. There is some evidence that maser disc emission is associated with AGN. Identifying AGN emission is not a trivial matter, however variability is a good indication for this phenomenon. In this presentation we use the Structure Function as a tool to quantify the variability in Mid-Infrared emission from galaxies with and without maser emission from their centers as a novel way of connecting AGN and maser emissions.

Active Galactic Nuclei (AGN) Physics

Active Galactic Nuclei (AGNs) are the ensemble of emission that comes from galaxy centers where supermassive black holes are actively accreting matter onto them. Although most galaxies contain a supermassive black hole, only ~10% have an AGN. Since black holes themselves are completely invisible, AGNs are extremely useful in determining the physical properties of black holes. (Lo 2005)





Messier 77
(astronomynow.com)

The torus surrounding the black hole is made of cosmic dust that obscures the visible light coming from excited and ionized clouds of gas that are normally used to identify the central source as an AGN. At the same time, it reprocesses radiation from the accretion disk (UV and X-rays) which is re-emitted in mid-infrared (mid-IR). (Lo 2005)

Megamaser Disks

Masers are Microwave Amplification by Stimulated Emission of Radiation. When detected in galaxy centers, and are 10^6 more intense than similar emission found in star forming regions, they are known as megamasers.

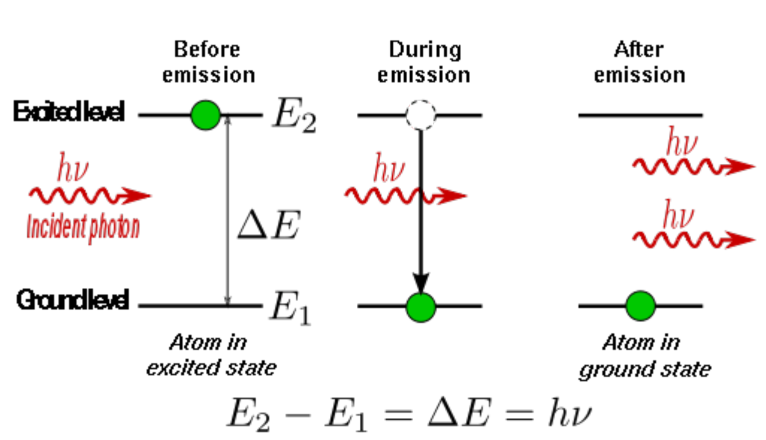
When in a disk-like configuration, there is some evidence that they are associated with seed radiation coming from an AGN.

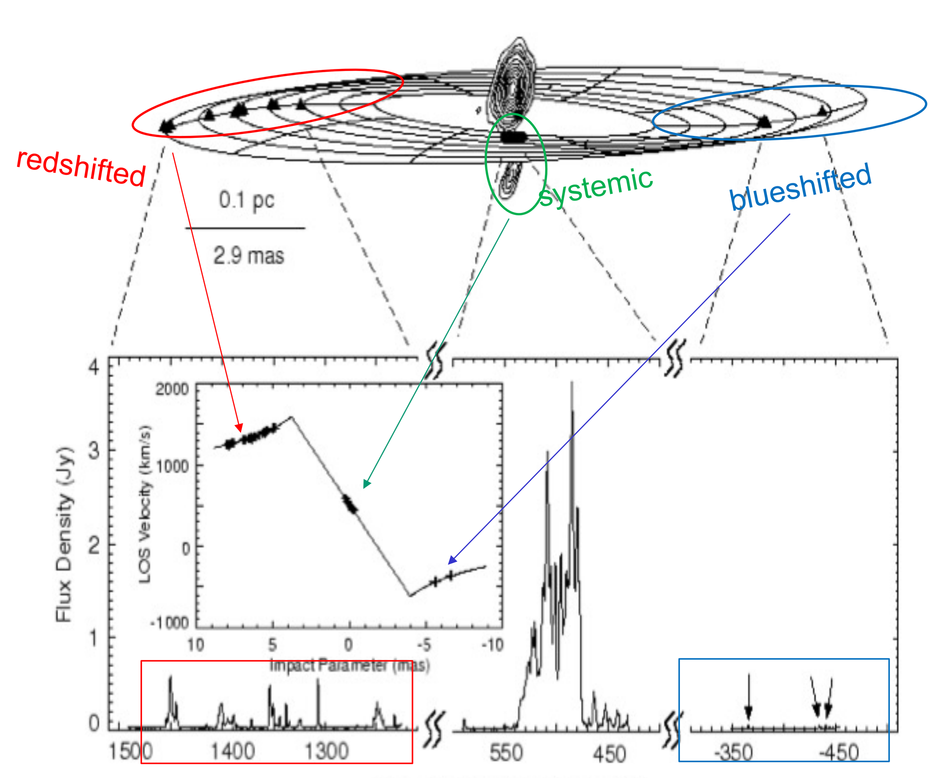
Measurements of their velocity as a function of their position provide a remarkable fit to Keplerian orbital motion, which in turn offer:

1. one of the most precise method for calculating the masses of supermassive Black Holes
2. direct calculations of distances to extragalactic cosmic objects.

Megamasers are extremely rare: detected in only < 3% of all galaxies surveyed for emission in 22 GHz.

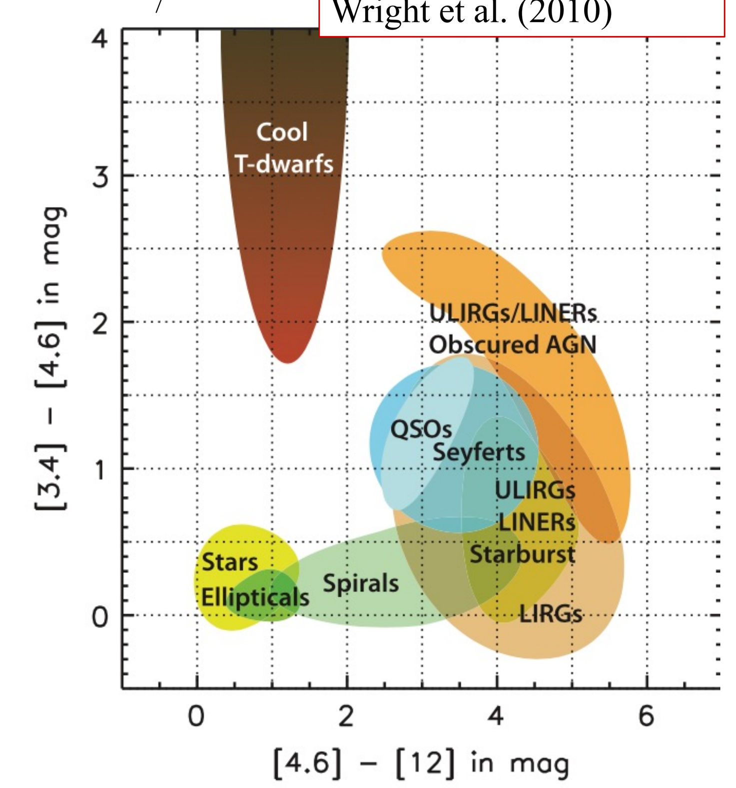
Only ~20% of all known megamasers are in a disk-like configuration. (Kuo et al. 2018)





Finding Active Galactic Nuclei in Mid-Infrared

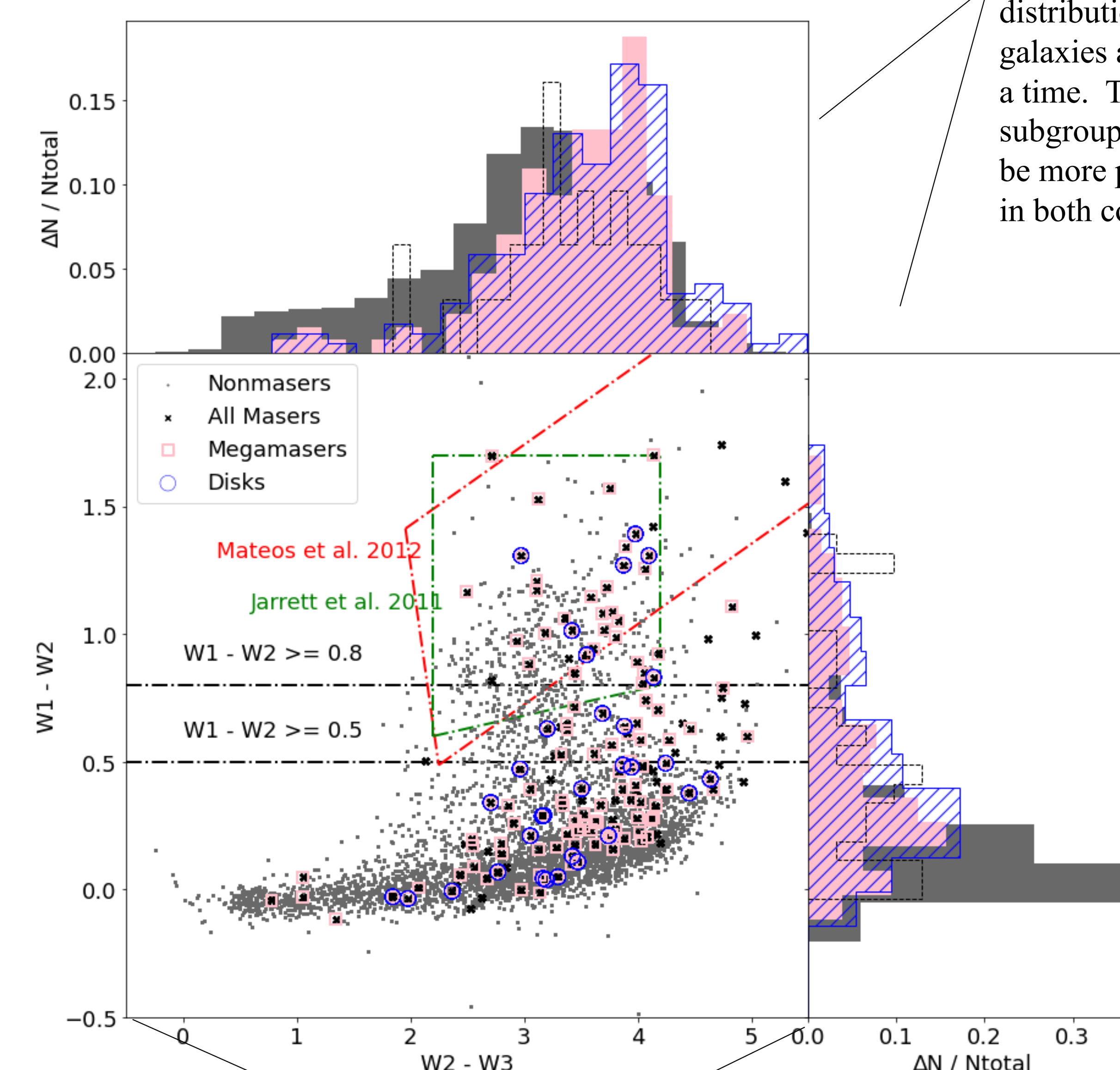
A color-color diagram displays the locations of different types of cosmic objects in terms of their mid-IR emission (from Wright et al. 2010). Note that the AGN-type sources (QSOs, Seyferts, ULIRGs, LINERs and Obscured AGN) are among the sources with redder mid-IR colors. (Wright et al. 2010)



The mid-IR observations are from The Wide-field Infrared Survey Explorer (WISE) which measured the sky in four bands (W1, W2, W3, and W4, centered at 3.4, 4.6, 12, and 22 micrometers, respectively).

The mid-IR emission comes from reprocessed radiation by circumnuclear dust in galaxy centers, and when is redder, it indicates a likely seed radiation coming from an AGN, proving thus especially useful in detecting obscured AGNs that remain elusive in other wavelengths. (Wright et al. 2010)

Histograms displaying the distributions of various types of galaxies as a function of one color at a time. The megamasers, and their subgroup of disk masers appear to be more prevalent among the redder in both colors.



The mid-IR color-color diagram showing the distributions of nonmasers, masers, megamasers, and maser disk galaxies, along with four criteria for AGN identification reveal that maser galaxies are somewhat equally found among mid-IR AGNs and non-AGNs (see tables with maser detection rates as a function of the AGN classification criteria).

	All Masers	Megamasers	Disks
W1 – W2 >= 0.8	**10%**	8%	2%
W1 – W2 >= 0.5	**9%**	7%	1%
Mateos et al. 2012	**8%**	6%	2%
Jarrett et al. 2011	**8%**	7%	2%

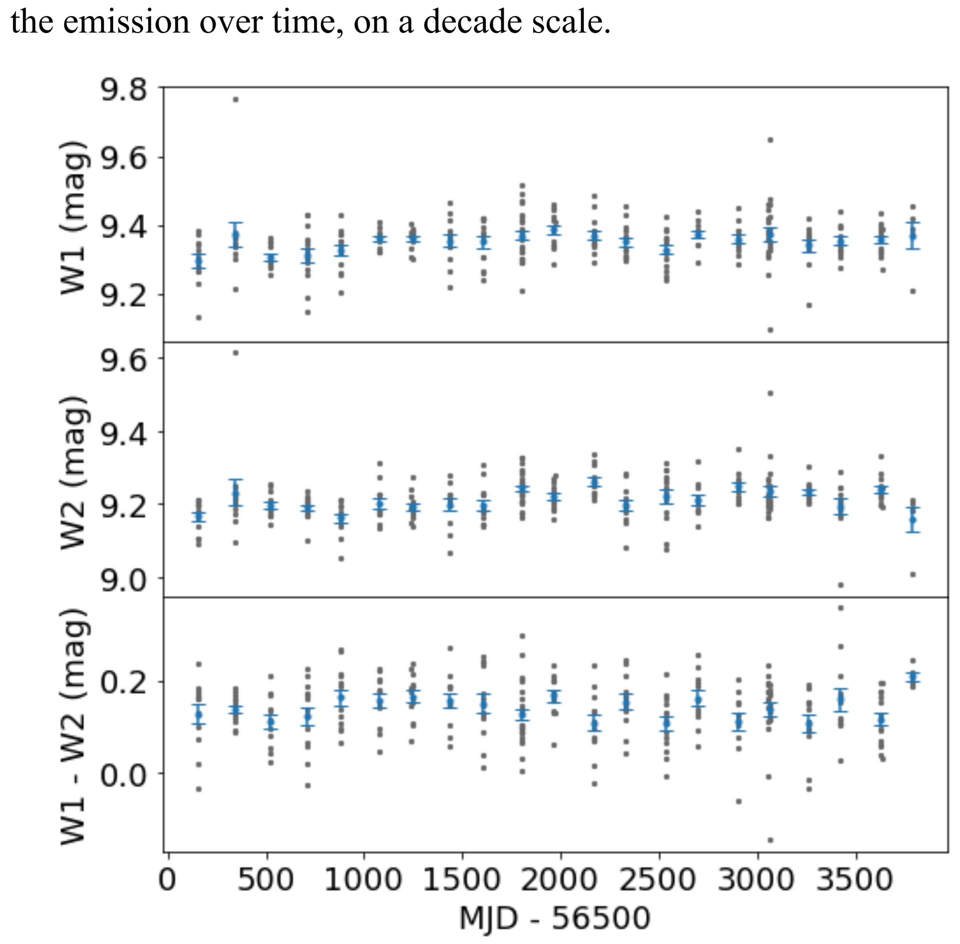
The detection rates for maser, megamaser, and disk galaxies for regions in the color-color diagrams identified as likely to host AGNs (red colors characterized by W1-W2 > 0.5 or a more stringent condition of W1-W2 > 0.8, as well as the wedges defined by Mateos et al. 2012 and Jarrett et al. 2011) reveal higher fractions than previously found in other types of maser host galaxies, supporting a relationship between maser emission and AGN activity.

Nevertheless, maser emission is still found in a significant fraction of galaxies that are blue in their mid-IR colors, or are outside the previously defined mid-IR color wedges (e.g., *Maser disks are equally likely to populate red mid-IR AGNs as blue galaxies*), suggesting that a simple selection of candidate maser galaxies based on mid-IR colors alone is not much more efficient than previous methods, so other ways of connecting the maser and the AGN activities are needed.

	All Masers	Megamasers	Disks
W1 – W2 < 0.8	3%	2%	1%
W1 – W2 < 0.5	3%	2%	1%
Outside Mateos et al. (2012)	3%	2%	1%
Outside Jarrett et al. (2011)	3%	2%	1%

New Ways of Identifying AGN: Variability

A few years after the WISE retired, the satellite was brought back for a new mission (NEOWISE) to record near earth objects such as asteroids. The NEOWISE also provided multi-epoch observations of all the WISE detections. This multi-epoch data can be used to investigate the time variability, i.e., the change in the intensity of the emission over time, on a decade scale.



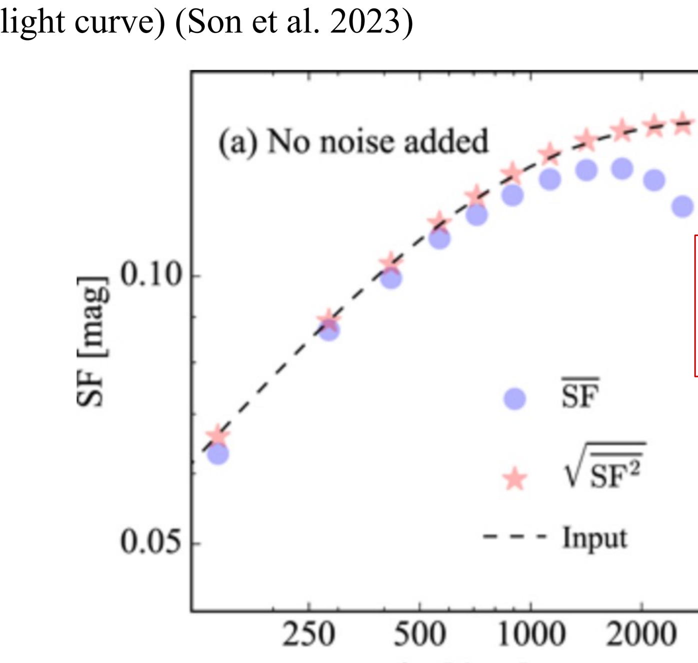
This plot shows the light-curve in W1, W2 and the W1-W2 color measured for [NGC23] Galaxy: the intensity of light emitted in the W1 and W2 band passes, in units of magnitudes (smaller numbers mean more intense flux), as well as the W1 – W2 color (lower numbers indicate bluer colors), are shown at different epochs (measured in Mean Julian Days, MJD). The number 56500 corresponds to the MJD of the start of the NEOWISE observations. The black dots are the individual measurements, while the blue bullets are the averages (along with standard deviations) for the binned data.

Quantify Variability

Quantifying the Variability: The Structure Function (SF)

$$SF^2(\Delta t) = \frac{1}{N_{\Delta t,pair}} \sum_{i=1}^{N_{\Delta t,pair}} (m(t) - m(t+\Delta t))^2 - (\sigma_e^2(t) + \sigma_e^2(t+\Delta t))$$

- $N_{\Delta t,pair}$ is the number of pairs associated with Δt (Δt is the change in value on the x-axis of the light curve) (Son et al. 2023)
- m is the observed magnitude as a function of time (the magnitude is the y-axis on the light curve) (Son et al. 2023)
- σ_e is the standard deviation of the multi-epoch data (from the error bars on the light curve) (Son et al. 2023)



An example of a Structure Function calculation from Son et al. (2023)

References: **Braatz, J.,** et al., 2009, ApJ, 695, 287; **Braatz**, et al., 2018, https://safe.nrao.edu/wiki/bin/view/ Main/Megam aserCosmologyProject; **Herrnstein**, et al., 1999, A&A, 20, 165; **Jarrett, T.,** et al. 2011, ApJ, 735, 112; **Kuo, C.,** Constantin, A., et al., 2018, ApJ, 860, 169; **Lo, K.,** 2005, ARAA, 43, 625-76; **Mateos, S.,** et al. 2012, RAS, 426, 3271-3281; **Son, S.,** Kim, and . Ho, L. C., 2023, ApJ, 958 135; **Stern, D.,** et al., 2012, ApJ, 753, 30; **Wright E.,** et al., 2010, AJ, 140, 1868;

Acknowledgements This work has been supported by JMU's Physics and Astronomy Department. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.