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NED for a New Era

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Abstract. The NASA/IPAC Extragalactic Database (NED[1]) is a thematic, on-line research facility that supports scientists, educators, space missions, and observatories in planning, data analysis, discovery, and publication of research on extragalactic objects. NED's ongoing mission is to provide a comprehensive and easy-to-use, multi-wavelength fusion of fundamental data for all known (cataloged and published) objects beyond the Milky Way. The contents and services span the entire spectrum from gamma rays through radio frequencies, and they are continuously updated to reflect the current literature and releases of large-scale sky survey catalogs. After a brief overview of NED's primary features, we review current developments that are vastly extending the content and capabilities of NED for our modern era of research involving very large, multi-dimensional, multi-wavelength data sets in the context of an interoperable, global Virtual Observatory. We then illustrate how researchers can program various types of queries to NED and retrieve machine readable tabular output using modern programming/scripting languages, and review how developers around the world are integrating content from NED Web services into various applications. We close with a discussion of the challenges for managing increasingly large and diverse data sets while maintaining quality in NED operations, which are centered around the core activity of establishing cross-identifications and relating information from thousands of journal articles and catalogs containing observations of hundreds of millions of extragalactic objects and candidates.

1. Introduction

NED provides the astronomical community with fundamental data, metadata, and well established relationships between multi-wavelength observations of tens of millions of extragalactic objects. NED strives to maintain a comprehensive, panchromatic census of all known objects in the extragalactic Universe, and their basic attributes. Team activities focus on establishing high fidelity, multi-wavelength cross-identifications (cross-IDs) and statistical associations, fusion of fundamental galaxy parameters, and data relationships that are persisted, served, and constantly revised as new literature and survey catalogs are published. NED provides human and computer programming interfaces into its own database, as well as seamless connectivity with distributed data centers and service providers. NED has been on the Internet since 1990, growing in content and capabilities with the evolution of information technology. NED spans across all missions, surveys and wavelengths, and is searchable by source name cross-identifications in different multi-wavelength surveys, redshift ranges, multiple

[1]http://nedwww.ipac.caltech.edu/

object types (e.g., QSOs, galaxies, radio sources, X-ray sources), combinations of source parameters, and journal article author. Essential data include positions, redshifts, morphological and spectral types, sizes, photometry, images and spectra. Photometric data are stored in original units and converted to common flux density units to construct spectral energy distributions (SEDs) spanning gamma-ray through radio wavelengths. Measurements are stored with uncertainties when available, and the data are dynamically linked to the on-line, peer-reviewed literature.

NED has been on the Web since 1997. VT-100 (ASCII) and UNIX/X-Windows client-server interfaces were supported when NED appeared on the Internet in 1990; these were retired in 2004. A batch mode that supports query requests via email form submission has been in service since 1992 and remains heavily utilized. Since 1994, NED has also supported a *server mode* with a client C library that is used by remote data centers and observatory operations to resolve extragalactic object names into celestial coordinates, and to perform object searches. For reasons explained in Section 5.2, the C server mode is being superseded by VO compatible Web services.

Astronomers working on extragalactic research use NED in their research nearly every step of the way; this includes proposal planning, data collection at the observatory, data analysis and interpretation, publication, and archiving of images and spectra. As of 2006 October over 4800 journal articles have acknowledged NED as an important resource. Many astrophysics data centers and researchers access NED's services from client software. Educators use NED in their lesson plans, and students use NED as a resource for learning.

2. Major NED Activities

The NED work flow begins with identification of sky survey catalogs and journal articles containing data relevant to extragalactic objects and candidates. Digital data are reformatted for the cross-identification process and entry into NED; this is done using a combination of scripting/programming and spreadsheet/database macros; in some cases manual table editing is still most efficient. Cross-identification and association of millions of entries in catalogs and publications is performed using a combination of computer software that utilizes positional uncertainty ellipse information to compute likelihood measures, followed when necessary by human inspection to resolve complex cases that cannot be fully automated. The database contents and relationships are revised and augmented continuously to keep up with new survey data and knowledge appearing in the literature. Updates to the public database occur approximately every three months after periods of data entry, quality assurance, and testing. Other important activities are the design of new services, development and testing, maintenance of the database and user interface software, and providing user support.

The NED staff works in collaboration with many organizations and individuals. We have numerous collaborations with other NASA data centers (ADS, HEASARC, IRSA, STScI/MAST), the CDS (Strasbourg, France), journal editors, and authors. The number of objects studied in journal articles are provided to ADS to keep the links to NED current. NED staff participate in the IAU

Working Groups on Nomenclature, Data and Journals. The Working Group on Designations of IAU Commission 5 clarifies existing astronomical nomenclature and helps astronomers avoid problems when designating their sources; the current Chair is NED operations lead M. Schmitz. In collaboration with the AAS journal office and CDS (Schwarz 2005), we participate in a process to enable authors to more easily publish valid and unambiguous source names and coordinates. NED personnel collaborate in various NVO developments. The NED staff is also in contact with authors of journal articles almost daily to resolve discrepancies, clarify ambiguities, and correct errors. This is just a sampling of ongoing collaborations with our community of service providers and users.

3. NED Services

3.1. Major Query Types and Data Services

Objects can be queried *By Name* (any alias) using the NED name interpreter, *Near Name* or *Near Position* (cone search), and *By Refcode* (reference). *Advanced All-Sky* (or, *By Parameter*) queries construct samples of objects using joint constraints on redshift, sky area, object types, survey names, cross-IDs, and flux density or magnitude. Available data include positions, redshifts, morphological and spectral classifications, photometry, distances, images, spectra, diameters, cross-IDs, associations, reference abstracts, and detailed notes. Uncertainties are included when available, and all information is cited and linked to the on-line literature via the Astrophysics Data System (ADS). References can be queried *By Object Name*, *By Author Name*, or via *Text Search*. Other tools include a *Coordinate Calculator* that performs conversions and precession and displays line-of-sight Galactic extinction estimates; a *Velocity Calculator* that converts between heliocentric, local-group, Galactic standard-of-rest, and 3K cosmic microwave background (CMB); and an *XY-Offset to RA/DEC Converter*. Users are shielded from the complexities of SQL by the NED software and interface.

3.2. Sample Building: Joint Constraints with SQL Hidden

The NED *All-Sky* query service supports joint constraints on redshift, flux density (or magnitude), object types, survey membership (including multiple cross-IDs), and sky area. The query dynamically generates a source table containing the best available source positions and redshifts, and includes links to references, photometry, redshifts, cross-IDs, associations, and images. With this service, users are querying the entire master index of unique sources, including optional constraints on N-way cross-IDs. For many studies it is more efficient to cross-correlate new observations against the data fusion in NED as opposed to N separate cross-comparisons to N separate catalogs in their original published forms. For example, a 3-way cross-ID between sources in the GOODS, SMM and TMRK surveys can be quickly extracted: 26 objects meet these criteria. All known objects with a measured redshift greater than 4.0 can be extracted in seconds; as of 2006 December, 3896 objects meet this criterion. More working examples are documented in the Tutorial section of the *All-sky* user interface.

3.3. SEDs

Several years ago NED pioneered the introduction of SEDs in astronomical Internet services. With over 25 million photometric measurements spanning 20 orders of magnitude in frequency (gamma rays through radio), NED serves the most extensive collection in the world. SEDs can be constructed only after the first, necessary step of establishing reliable cross-IDs among observations in different catalogs and journal publications; NED does this. The data are maintained in their original units and converted to standard units to enable SED construction. The data are fully referenced and include uncertainties where available. The SED plots are dynamically generated with configurable units, error bars, labels and zoom capabilities. Output formats include VOTable (XML) and simple ASCII tables. See Mazzarella, Madore, & Helou (2002) for a more detailed discussion.

3.4. Image Database

NED offers an extensive image database that is used widely and greatly facilitates multi-wavelength studies. Its primary goal is to provide a repository of images contributed by authors of journal articles; the journal papers themselves publish only images rendered as contours and gray-scale plots. These are high-level data products generally unavailable in mission archives or elsewhere. The system also includes galaxy images from DSS, 2MASS and other large surveys. In addition to queries by object name and areal coverage using the Web interface, NED's image archive is accessible from applications such as the *HST* APT[2], *Spitzer* SPOT[3], OASIS[4] and Aladin[5]. The image database can also be queried via the VO-compatible Simple Image Access Protocol (SIAP).

3.5. LEVEL 5

LEVEL 5 is a knowledgebase[6] for extragalactic astronomy and cosmology. Contents include a glossary of terms, essays, research articles, and extensive reviews (where copyrights allow). Within each article, named extragalactic objects are cross-linked to directly query NED, and citations are hyper-linked to ADS. Recent additions are summarized in the NED news[7].

3.6. Connectivity

Fundamental data and relationships are stored directly in NED, but much more information is connected using pointers to remote archives. NED links major archive centers (e.g., HEASARC, MAST, IRSA, CDS, NRAO) and the literature (via ADS) in an easy-to-use fashion utilizing source names, survey/catalog

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[2]http://www.stsci.edu/hst/proposing/apt/

[3]http://ssc.spitzer.caltech.edu/propkit/spot/

[4]http://irsa.ipac.caltech.edu/applications/Oasis/

[5]http://aladin.u-strasbg.fr/

[6]http://nedwww.ipac.caltech.edu/level5/

[7]http://nedwww.ipac.caltech.edu/help/whats_new.html

cross-identifications, and sky positions as the glue between data sets. The External Archives and Services section of NED query result pages contains simple, one-click access to distributed images, catalog data, and observation log entries. The user can retrieve images, catalog data, or observation log entries from original catalog record entries in VizieR (CDS/France and mirrors); NVSS, FIRST catalog and image servers, VLA Observation Log from NRAO; Infrared mission archives at IRSA/IPAC (e.g., 2MASS, *IRAS*); Visual and UV mission archives at STScI/MAST (e.g., *HST*, *IUE*, *GALEX*); high energy mission archives at HEASARC (e.g., *ASCA*, *CGRO*, *Einstein*, *Chandra*). New services are added as they become available. Plans for the near future include more comprehensive links and VO compatibility; however, NED will continue to provide thematic, focused connectivity based primarily on extragalactic source cross-IDs. NED's seamless connectivity to globally distributed resources serves as a thematic Virtual Observatory portal. Distributed services are also highly connected to NED. Observatory control systems, various Internet sites and observation planning applications query NED for a variety of data, including positions, redshifts and basic data about galaxies, name-to-coordinate resolution, images, etc.

4. Database Contents

NED content highlights as of 2006 October are as follows (a scale factor showing growth since 2002 is listed in parentheses for reference): 9.4 million unique objects (2.5×); 14.5 million multi-wavelength catalog cross-IDs (3×); 25.2 million photometric measurements spanning gamma rays through radio frequencies (7×); 3.6 million detailed size measurements with uncertainties (there were none in 2002); 3.5 million object pointers to 63,000 journal articles (2×); 1.2 million redshifts (7×); 2.3 million FITS images, maps and links with previews (18×); 65,000 detailed notes from catalogs and journal articles (1.4×); and 41,000 journal article abstracts (2×). A current contents summary is always available on the NED home page, supplemented by information in the news page.

5. Recent Developments

5.1. VO-Compatible Services

As of 2006 January, all major NED Web services offer an output mode that provides results in VOTable XML document trees. The services can be accessed directly at the NED Web interface, or by using the NVO Registry and harvesting methodologies (Green et al. 2003). The VO-compatible services include queries to the NED image archive via Simple Image Access Protocol (SIAP), object searches using the Cone Search protocol, and 16 specialized Web services providing fundamental data and multi-wavelength relationships that can be filtered using various constraints. The meaning of the various query filters can be easily determined from the corresponding input form and help files on the NED server, or by using the ReferenceURL from the NVO Registry search result. For example, a VOTable containing the SED for the galaxy 3C 279 can be queried via `http://nedwww.ipac.caltech.edu/cgi-bin/nph-datasearch?objname=3c279&of=xml_main` with corresponding documentation

`http://nedwww.ipac.caltech.edu/forms/photo.html` (input), and `http://nedwww.ipac.caltech.edu/help/phoresult_help.html` (output). Pevunova et al. (2005, Figure 3) illustrated the process of running the above photometry query and displaying the resulting SED using VOPlot. The available data span 17 orders of magnitude in frequency coverage, from 38 MHz (radio) to 1.48×10^{24} Hz (*EGRET* 4–10 GeV gamma rays). For a second example, one can run a *By Parameter* (all-sky) query with various filters and view the positions of the qualifying sources using VOPlot. VOTable is also used to provide standardization of the spectra provided to NED in various ASCII and FITS formats by authors of journal articles; this allows the spectra to be visualized, analyzed, and combined using the *Specview* Java applet (Busko 2000). Section 5.6 presents further discussion about NED's new spectral database.

5.2. Updating Connectivity to NED from Client Programs

NED web services use the HTTP GET protocol whenever possible, with query filters encoded as URL name–value pairs. This allows users to embed queries to NED easily in web pages, simplifies automated connections from nearly any modern programming or scripting language, and enables access via simple utilities such as **curl** or **wget** for users with limited programming abilities.

Numerous web services, observation tools and computer programs developed by astronomers around the world use the legacy NED *server mode* (on port 10011) for direct connectivity to NED. This NED service has been supported for over a decade. But for the following reasons we encourage people developing new client applications, or maintaining old ones, to utilize the new NED VO Web services. The legacy C client-server mode for access to NED is quite limited in the queries supported and in the supplied data; also, it is no longer being enhanced. Client access via Web VO services provides access to nearly all NED services and content, minimizes problems with local firewalls (since connections are via port 80), access is available from any computer language that can access HTTP URLs (and is not restricted to the C language), and any XML/VOTable parser can be deployed (rather than handling a custom data structure). There are a number of recent developments in this area. The *Spitzer* Planning Observations Tool (SPOT, and its derivatives iSPOT and HSPOT) developed at the Spitzer Science Center and IPAC are being upgraded to utilize the NED Web VO services. The NVO data discovery and browsing tool DataScope[8] connects to a number of NED VO services (via the Registry). Source name-to-coordinate look-up (*name resolution*) is a key component under the hood of the main NVO site[9] and in other emerging VO portals; these are successfully using NED's modern Web services rather than the legacy C server.

5.3. Extragalactic Distances: NED-1D

In 2006 June NED released an extensive compilation of extragalactic distance measurements named NED-1D[10]. The primary goal is to provide rapid and effi-

[8] http://heasarc.gsfc.nasa.gov/vo/

[9] http://www.us-vo.org/

[10] http://nedwww.ipac.caltech.edu/level5/NED1D

cient access to a comprehensive and easy-to-use ensemble of published distance measurements tightly linked to the literature and NED. Version 1.1 contains 3,065 contemporary distance measurements to 1,073 galaxies with recessional velocities less than $0.125c$, as published between 1990 and 2006. The distance methods covered include: (1) Cepheid periodicity-luminosity relation, (2) tip of the Red Giant Branch (i.e., *I*-band luminosity function cut-off), (3) planetary nebula luminosity function, (4) globular cluster luminosity function, (5) surface brightness fluctuations (*I*-band), (6) supernovae of type Ia, (7) brightest star luminosities, (8) "look-alike" galaxies, (9) Tully-Fisher relation, (10) fundamental plane, and 25 less common methods. Integration of galaxy distances from NED-1D into NED object queries will appear in a future upgrade.

5.4. Corrected Velocities, Distances & Cosmological Quantities

One of the most frequently requested enhancements to NED is now available: corrected velocities (redshifts) and distances derived from the Hubble flow and a standard cosmological model. Heliocentric redshifts are corrected for Galactocentric GSR (RC3), Local Group (Karachentsev & Makarov 1996), 3K CMB (*COBE* FIRAS: Fixsen et al. 1996), Virgo SC in-fall (Mould et al. 2000), and Virgo SC, Great Attractor, Shapley attractor model in-fall (Mould et al. 2000). In addition, cosmological corrections are offered with documented computations. The results are included in the output for any object with an available redshift, for example after a *By Name* or *Near Name* (cone) search. Insertion of these derived quantities into tabular output for galaxy samples is in development. There are also plans to allow users to over-ride the default cosmological parameters.

5.5. Literature Data Content & Topical Keyword Filters

Over the years, NED users have asked for a way to filter the rapidly growing literature, based on data content and specific extragalactic topics. NED contains substantial information about the data content of journal articles. Thus, using semi-automated methods, this information is being used to assign keywords in these categories: Classifications, Diameters, Components, Images, Photometry, Kinematics, Object Notes, Positions, and Spectroscopy (redshift). This information often cannot be extracted from titles and abstracts alone, but requires knowledge of the content of tables, figures, etc. The computer science literature contains debates on the merits of free-text search versus use of a "controlled vocabulary" (keywords) assigned by analysis of a knowledge domain. The latter often results in more precise results due to normalization of terms. For example, "starburst" = "H II" (context: nuclear spectrum), or "ultraviolet" = "UV". NED is now assigning and displaying Data Content Keywords (for all papers) and Topical Keywords (currently only for pre-2000 papers via ARIBIB[11]). Both keyword sets are displayed and utilized in new (optional) filters on literature searches based on object names or author names.

[11] http://www.ari.uni-heidelberg.de/aribib/

5.6. Spectral Database

In 2007 January NED will release a new spectral database. This service provides: (1) a unique repository for spectra previously published only via rendered plots in journal articles, patterning after the success of NED's image archive; (2) preview plots; (3) preservation of the original data format provided by authors and archive curators; (4) standardized (MKS) units and a uniform VO-compatible data format; (5) ASCII and VOTable download options; (6) a query service to locate spectra by object name, journal article (*refcode*), passband, line filters, and combinations thereof; (7) quick-look visualization and analysis capability; (8) interoperability with VO. VOTable is used to standardize the data structure and physical units of spectra provided in various FITS and ASCII formats. This also facilitates comparison, fusion and analysis of spectra via VO-compatible applets such as Specview and VOPlot.

6. Challenges for Quality Assurance

6.1. Quality vs. Quantity: Can We Have It All?

Automated tools for the production of "pipeline" source extractions (e.g., SExtractor) are used extensively in modern astronomy. However, shredding the galaxy images into bits that often do not correspond to real, physical subcomponents of the galaxies is a major complication for any attempt to fully automate source cross-IDs. There are still significant systematic offsets in astrometry among sky surveys, although this problem is diminishing. Incremental data releases for large sky surveys is another modern fact of life. Improved processing often leads to small but significant revisions in positions, which changes the source IDs (position-based names) and thus affects cross-IDs. For example, there are some SDSS objects in NED published with four different identifiers. Revisions in flux calibration and astrometry produce multiple instances that are not independent observations, which complicates the data fusion process, confounds the resulting SEDs, and produces other complexities in the database. Often data providers do not perform band-merging or merge the same objects in overlapping fields; they publish "sub-catalogs" extracted from different images. Therefore, others (NED, individual researchers) are left to figure out the cross-IDs and either remove or annotate duplications.

6.2. The Need for Peer-Reviewed Data

The literature remains a key source of unique and ground-breaking data. However, data appearing in journal articles are not refereed to the same degree as the science results and the text. Often published URLs to data sets no longer exist, or the data are poorly formatted, contain major errors, or have insufficient metadata for understanding the contents. Other practical issues are that some astronomers move frequently, lose interest in datasets after publication, and often cannot afford to repair failed computers. Therefore, while the concept of astronomers self-publishing data sets is technologically feasible, this is likely to lead to a chaotic and unstable VO. This underscores the continued importance of dedicated teams of people operating data centers and thematic portals, curating data and persisting relationships as part of a robust and long-lived VO.

A related problem is that standard nomenclature and unambiguous coordinates for objects are encouraged but not enforced by editors and referees, leaving NED with a lot of clean-up work. The NED team has participated in steps to rectify this problem in collaboration with the U.S. journals (Schwarz 2005); the largest challenge is achieving active and consistent participation from authors.

6.3. High Fidelity Cross-IDs are Non-Trivial

Surveys with different telescopes and wavelengths vary in fundamental ways, including sensitivity, angular resolution, and calibration uncertainties (astrometry and flux). For example, a galaxy pair resolved at 2 μm may be unresolved at 24 μm. Astrophysics makes sources look different as a function of wavelength; for example, in dusty starburst galaxies, centroids in the IR often do not match those in the UV. In addition, objects reside in a hierarchical Universe: galaxies contain components (AGNs, supernovae, star clusters, HII regions, etc.); galaxies occur in pairs, group and clusters; and clusters string together in superclusters separated by vast voids. Often statistical associations are needed because confident cross-IDs are not always possible with available information. While completely automated and real-time cross-IDs among distributed data sets has a role in the VO, we must also acknowledge the importance of a careful, high-fidelity approach that takes into account position uncertainties, spatial resolution (beam size) differences, object sizes, group memberships, SEDs, differing source densities at different wavelengths and flux limits (confusion), and eventually provisions to include prior knowledge (using Bayesian statistics). Refinements need to be established as new knowledge becomes available, and the extensive science expertise and archive work involved needs to be persisted and served as the foundation for reliable cross-IDs with the next generation of observations. Extensive automation, augmented by human expertise where programmable procedures reach their limit, is one of NED's primary strengths.

7. Summary

NED's content, services, and interoperability are evolving rapidly. The storage, servers, and request management system is scaling up to support large-scale queries and statistical astronomy involving hundreds of millions of galaxies. Numerous VO-compatible NED services used in concert with other components of the emerging VO empowers astronomers with extensive tools to automate queries and analyze multi-wavelength data. Three new services will appear in 2007 January: (1) data for galaxies include dynamically computed velocities (redshifts) corrected for local flow motions, distances and scales based on the Hubble flow, as well as cosmological distances and look-back times; (2) a new spectral database with unique content, query capabilities, quick-look visualization and VO compatibility; (3) keyword filtering of journal articles based on data content as determined by NED, and topical keywords based on a vocabulary relevant to extragalactic astrophysics as established by ARIBIB. Finally, we reviewed limitations to automation and discussed the importance of a blend of computer automation and human expertise to maintain quality assurance in federated data, and to provide user support. In this era of escalating growth in

data and complexity, NED is continuing its evolution as a major astronomical research facility in its own right, and as a key VO service provider and portal.

Space limitations prevented inclusion of illustrations for even just a subset of the new NED services. Extensive graphics illustrating most of the services discussed in this paper may be viewed in the 2007 January NED handout[12]. The reader is also encouraged to use them directly on the NED interface.

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[12]http://nedwww.ipac.caltech.edu/docs/NED2007JanHandout.pdf