A Catalog of Stellar Unified Properties (CATSUP) for 951 FGK-Stars within 30 pc

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Abstract

Almost every star in our Galaxy is likely to harbor a terrestrial planet, but accurate measurements of an exoplanet’s mass and radius demand accurate knowledge of the properties of its host star. The imminent TESS and CHEOPS missions are slated to discover thousands of new exoplanets. Along with WFIRST, which will directly image nearby planets, these surveys make urgent the need to better characterize stars in the nearby solar neighborhood (<30 pc). We have compiled the CATalogue of Stellar Unified Properties (CATSUP) for 951 stars, including such data as: Gaia astrometry; multiplicity within stellar systems; stellar elemental abundance measurements; standardized spectral types; Ca II H and K stellar activity indices; GALEX NUV and FUV photometry; and X-ray fluxes and luminosities from ROSAT, XMM, and Chandra. We use this data-rich catalog to find correlations, especially between stellar emission indices, colors, and galactic velocity. Additionally, we demonstrate that thick-disk stars in the sample are generally older, have lower activity, and have higher velocities normal to the galactic plane. We anticipate that CATSUP will be useful for discerning other trends among stars within the nearby solar neighborhood, for comparing thin-disk versus thick-disk stars, for comparing stars with and without planets, and for finding correlations between chemical and kinematic properties.

Key words: catalogs – solar neighborhood – stars: abundances – stars: fundamental parameters – ultraviolet: stars – X-rays: stars

Supporting material: machine-readable table

1. Introduction

The acceleration of exoplanet detections has shifted the field from one of discovery to one of characterization. Surveys are rapidly becoming complete with respect to Jupiter-sized planets: occurrence rates of gaseous giant planets with masses >50 M_J and periods <10 years are ∼14% (Mayor et al. 2011). Even the discovery of Earth- to super Earth-sized (radii 0.5–4 R_E) planets is becoming routine, with an occurrence rate ∼1 per small star inferred (Dressing & Charbonneau 2013, and references therein). The Kepler mission has established that planets are nearly ubiquitous around stars, and even multi-planet systems are common (Batalha et al. 2013). Kepler has discovered about 550 rocky exoplanets, including 9 that orbit in their stars’ habitable zones (Kepler press release 2016 May 10). Scientific progress in the field of exoplanets has advanced so much, in fact, that it is possible to go beyond asking where the planets are and to ask what they are made of, a necessary first step toward assessing habitability. Finding and characterizing exoplanets are the goals of future space missions such as the Transiting Exoplanet Survey Satellite (TESS), the Characterizing ExOPlanets Satellite (CHEOPS), the PLAnetary Transits and Oscillations of stars (PLATO) mission, and the Wide-Field InfraRed Survey Telescope (WFIRST).

It is a truism in the exoplanet community that to know the planet one must know the star. Detection of exoplanets has always depended on good characterization of the star. This was true of 51 Pegasi (Gray 1997), and the recent case of HD 219134h, where a planet inferred by Vogt et al. (2015) was found to have a period equal to the star’s rotation period, making it an artifact of stellar activity (Johnson et al. 2016). To meaningfully constrain exoplanet compositions, one needs to distinguish a bulk density of 2 g cm⁻³ (like the densities of Ganymede and Titan, made of rock and ice per Showman & Malhotra 1999) from one of 5 g cm⁻³ (like the densities of Mercury, Venus, and Earth, with metal cores and rocky mantles per Wanke 1981). To measure density at this precision requires constraining planetary mass and radius, and therefore stellar mass and radius, to within about 10% (Unterborn et al. 2016). In order to move beyond simple questions of whether a planet is rocky with ice or rocky with a large metal core, the inclusion of elemental ratios, inferred from the host star, must be included. The habitability of the planet, and the detectability of life through atmospheric gases, depend on the state of the atmosphere, which is sensitive to high-energy (X-ray and ultraviolet (UV)) emission from the star. At every step, characterization of an exoplanet requires comprehensive information about the host star.

A wealth of information currently exists for the Sun-like (main sequence, FGK-type) stars within 30 pc that will be the highest priorities for exoplanet searches and observations. We examine stars within a radius 30 pc to ensure a certain quality sample of stars that is “complete” for the targets of highest priority direct imaging missions (early/mid-KV and brighter stars, V > 7–8 at the faintest). Beyond that distance, there is a decreased ability to detect stellar companions, which results in plummeting quality at the cost of exponentially more work in vetting the data from other sources on fainter and more distant stars. Yet, despite the availability of useful repositories such as
Vizier (Ochsenbein et al. 2000), PASTEL (Soubiran et al. 2016), and TOPCAT (Taylor et al. 2005), no single database contains all the disparate physical and chemical information needed to thoroughly characterize nearby Sun-like stars. What information exists is often spread across several non-standardized databases.

In response, we have created the CATalog of Stellar Unified Properties (CATSUP), where we combine important stellar information with the goal of expediting the characterization of planetary systems, their interior structure, and overall habitability. CATSUP incorporates available stellar information relating to astrometry, multiplicity, stellar activity, and stellar abundances with new, unpublished, high-energy emission data. Specifically, we have included new far-UV (FUV) and near-UV (NUV) emission data from the Galaxy Evolution Explorer (GALEX). We have also added X-ray data from the ROSAT, XMM, and Chandra missions that have been combined using a new methodology and put on a uniform baseline. Both UV and X-ray information is important when characterizing a planetary system and for understanding exoplanet atmospheres and their possible evaporation. The number of stars and breadth of data within CATSUP allows access to data that were previously difficult or inaccessible. Even when specific stars are not listed in the database, data can be cross-correlated in order to form a benchmark from which proxies can be determined based on similar, nearby stars. While we have chosen not to focus specifically on planetary properties within CATSUP, the information for solar neighborhood stars can be utilized to better characterize planets and their host stars. We particularly focus on collating data to assess planetary habitability, to help narrow the observational field, and to optimize the search for Earth-like planets, a particularly important goal as telescope time for follow-up observations is limited.

In this paper we discuss the creation and contents of CATSUP, a catalog of 951 nearby (<30 pc) FGK main sequence stars containing an array of data sets relevant to exoplanet detection and characterization. For data already available in the literature, we will briefly summarize the details in an effort to maintain a holistic view of the CATSUP database. We begin with the high-precision astrometric measurements by the Gaia mission (Gaia Collaboration et al. 2016) as the basis for the catalog (Section 2). We include currently available data on system multiplicity from ExoCat (Turnbull 2015, see Section 3), stellar abundance measurements from the Hypatia catalog (Hinkel et al. 2014, see Section 4), collated spectral types (Section 5), and Ca II H and K stellar activity indices (Smith 2011, Section 6). We present UV emission data from GALEX archives (Section 7). Finally, we present X-ray data from the ROSAT, XMM and Chandra missions (Section 8). As an example of the capabilities of the combined database, we present in Section 9 an exploration of the correlation between Ca II H and K indices with color, galactic velocity, and thin-disk versus thick-disk membership.

2. Gaia

The Tycho-Gaia Astrometric Solution (TGAS, Gaia Collaboration et al. 2016) subset of the Gaia survey provides a convenient and logical starting sample for which data important to both stellar and exoplanet scientific studies can be compiled. Despite the fact that TGAS is ~80% complete in reference to both Hipparcos and Tycho-2 (Arenou et al. 2017), the high-precision astrometry is valuable for target characterization. Additionally, one of the main reasons for TGAS’ incompleteness is a cut on stars with high parallax errors, namely >1 mas (Arenou et al. 2017), which is acceptable, if not preferable, given our intention. Therefore, we started by querying TGAS sources available through Vizier7 (Ochsenbein et al. 2000). We then placed a 30 pc cutoff, or parallax >33.33 mas, on the TGAS stars so that we could focus on nearby stars that have both physical and chemical measurements. Note that the distance provided was calculated as the inverse of the parallax, which is a safe assumption for nearby stars, as in this case, e.g., Astraatmadja & Bailier-Jones (2016). Then, using the MK classification of Skiff (see Section 5), we included only FGK-type stars in order to maximize completeness. In this way, CATSUP is able to better achieve catalog completeness by only including nearby main sequence stars with accurate astrometric solutions (Arenou et al. 2017).

The total number of stars with compiled data within CATSUP is 951, shown in Figure 1. By summing each of the separate ellipses, you will get the total number of stars in each data set: 879 stars in ExoCat, 534 in Hypatia, 627 with the Ca II H and K indices, 708 with GALEX UV data, and 364 with X-ray data. Furthermore, we have included a flag within Table 3 to indicate whether a star is known to host an exoplanet at the time of this publication, based on the NASA Exoplanet Archive.8 A summary of the parameters available in CATSUP is given in Table 3—the full table will be provided via the online journal and through Vizier. In the next sections, we describe the compilation of essential stellar data within CATSUP.

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7 http://vizier.u-strasbg.fr/viz-bin/VizieR-3?-source=1/337/tgas
8 Exoplanetarchive.ipac.caltech.edu. We found that 48 stars within CATSUP are currently known to host exoplanets.
3. ExoCat

The Nearby Stellar Systems Catalog for Exoplanet Imaging Missions (a.k.a. “ExoCat,” Turnbull 2015) was created for the purpose of supporting the development of exoplanet direct imaging missions such as WFIRST, Exo-S, Hab-Ex, and other concepts (Spergel et al. 2013, 2015; Seager et al. 2015; Mennesson et al. 2016, respectively). The current version of ExoCat contains 2351 entries for Hipparcos stars within 30 pc of the Sun. ExoCat provides basic observational data (e.g., Hipparcos astrometry including Equatorial and Galactic coordinates, parallax, and proper motions, Johnson B and V magnitudes, and Ks-band magnitudes from 2MASS or converted to 2MASS Ks magnitudes for bright stars). Using these data, ExoCat contains derived estimates of stellar luminosity, effective temperature, stellar radius and angular size, stellar mass, habitable zone locations and angular size, photometric fractional planet brightness and V-band magnitude for an exo-Earth at the Earth-equivalent insolation distance (see Turnbull 2015, for details). For bright stars (V < 7), ExoCat provides separations and delta-magnitudes for the brightest stellar companion within 10 arcseconds, taken from the Washington Double Star catalog (Mason et al. 2001).

All of these star and system parameters are crucial to understanding the necessary performance of an exoplanet imaging mission: from controlling stray light from off-axis companions, to setting requirements on contrast and speckle stability, inner and outer working angles, and throughput, to creating a design reference mission and observing schedule that can be executed within solar avoidance and other engineering constraints. ExoCat is under continuous development in order to provide more accurate system parameters. ExoCat-v1 can be downloaded from the Exoplanets Exploration Program (ExEP) website.7 There are 879 ExoCat stars within CATSUP, and 878 of those stars can also be found in the TESS Input Catalog (Stassun et al. 2017). Note that the TESS Input Catalog was the only target selection list available out of the three upcoming exoplanet missions (TESS, CHEOPS, and WFIRST).

One especially important and complicated piece of information involves binary and multiple systems. ExoCat contains a growing set of system descriptions identifying components that may not be included in Hipparcos (or for which the Hipparcos identifier refers to more than one star); these indicators have been included in CATSUP (see Table 3). Each star is noted as either (a) a true single star per a deep literature source (Table 3, Single = 1), or (b) if known to be a member of a multiple, which component that HIP number is referring to (Table 3, Component = A, B, etc.). In many cases, the HIP number includes more than one star, either a known or suspected unresolved/very faint companion, which is noted by a “+” symbol. In a few cases, the “+” has its own additional entry. If more than one star in the system has its own HIP number, the other associated HIP numbers are listed in the “HIP2” column. As noted in the original ExoCat paper (Turnbull 2015), if the “Single” column does not equal 1 or if there is a “+,” then it is possible that the system does not correspond to only one star. Namely, it is possible that the HIP entry corresponds to more than one object. If that system comes up as a high priority for a future mission, it should be scrutinized more carefully. Of the stars in our catalog with either known single or binary status, ~45% reside in binary or triple systems. This multiplicity fraction matches expectations from volume-limited companion surveys, which generally find that 45%–50% of main sequence stars in the mass range 0.7–1.3 M\(_\odot\) (a close match for the CATSUP catalog) are multiples. As a secondary check, we cross-reference CATSUP with the Tycho Double Star Catalog (Fabricius et al. 2002), finding that among the stars present in both catalogs, 49% have companions. We conclude that the binary fraction of our sample is consistent with expectations.

4. The Hypatia Catalog 2.1

The Hypatia Catalog is a composite stellar abundance catalog that is comprised of multiple literature sources of high-resolution spectroscopic data (Hinkel et al. 2014, 2016). Since the last update published in Hinkel et al. (2016), we have included 55 additional catalogs from the literature, as well as 11 new elements and species (namely: Si ii, Nb ii, Pr ii, Gd ii, Tb ii, Dy ii, Er ii, Tm ii, Yb ii, Hf ii, Th ii), as shown in Figure 2. A breakdown of the added data sets, including information regarding the telescopes, models, and techniques, is given in Table 2. There are currently 64 elements and species measured in 5986 main sequence stars within 150 pc of the Sun. Keeping with our naming scheme, we have increased the tenths value of the version number in order to indicate the addition of new data sets.

In addition to the data sets, we have included a number of new stellar properties within Hypatia and updated the source for some of the existing properties. Namely, we now take advantage of the high-precision R.A., decl., and parallaxes from Gaia, where applicable, or for ~68% of the Hypatia Catalog. For the remaining 32%, we continue our use of Anderson & Francis (2012) for the R.A., decl., and parallaxes not available in Gaia. Stellar effective temperature (T\(_{\text{eff}}\)) and surface gravity (log(g)) have been pulled from the PASTEL catalog (Soubiran et al. 2016), in addition to preferentially using their B and V magnitudes where possible. Finally, Hypatia now incorporates the 2MASS identifier. All properties and original sources of reference are listed in Table 3.

The full Hypatia Catalog Database, including stellar abundances from all individual catalogs, a variety of solar normalizations, stellar properties, and planetary properties (where available), can be found at http://www.hypatiacatalog.com. Multiple interactive plotting interfaces, in addition to tabular data, can be freely accessed through the website to quickly and easily analyze stellar abundance data, including an updated version to standard [X/Fe] versus [Fe/H] plots as a result of new abundance information incorporated into Hypatia. Additionally, data can be downloaded through the terminal for use in personal plotting routines.

For the analysis conducted here, each data set was normalized to the same solar abundance scale, namely Lodders et al. (2009), in order to minimize systematic differences between the varying methodologies. During those cases where multiple groups measured the same element abundance within the same star, the median value was taken and reported in CATSUP. The range of stellar abundance measurements by different groups is referred to as the spread, a value that often exceeds the individual error bar (Hinkel et al. 2014). Note that unlike previous applications of the Hypatia Catalog, abundance values were reported even when the spread in abundance determinations—or the range of measurements between groups (Hinkel et al. 2014)—was greater than a standardized error. The abundances for [Fe/H], [C/H], [O/H], [Na/H], [Mg/H],

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7 http://nexsci.caltech.edu/missions/EXEP/EXEPstarlist.html
[Al/H], [Si/H], [Ca/H], [Ti/H], [V/H], [Cr/H], [Mn/H], [Co/H], and [Ni/H], or elements that have been measured in over 4000 stars in Hypatia, have been included in Table 3. Additionally, the spread values for all elements in CATSUP can be found in Table 3, indicated as spXH. Similar to Figure 2, we have included a histogram of the total number of stars in CATSUP for which the 14 elements have been measured in Figure 4. A total of 534 stars within CATSUP had stellar abundances in Hypatia 2.1. All 534 stars can also be found in the TESS Input Catalog (Stassun et al. 2017).

The basic atmospheric parameters, \( T_{\text{eff}} \), \( \log(g) \), and \([\text{Fe}/\text{H}]\), are very important for the characterization of any stellar sample. Not only do \( T_{\text{eff}} \) and \( \log(g) \) define the physical conditions of the stellar photosphere, but they are fundamental to stellar abundance measurements. Additionally, stellar \( T_{\text{eff}} \) directly influences the temperature on a planetary surface while the abundance of \([\text{Fe}/\text{H}]\) impacts the planet’s interior structure and composition. When a CATSUP star was not within Hypatia, the \( T_{\text{eff}} \) and \( \log(g) \) were sourced from PASTEL; and if it was not found within PASTEL, the \( T_{\text{eff}} \) and \( \log(g) \) were found within ExoCat. In order to show the parameter space of \( T_{\text{eff}} \) in CATSUP, we have plotted a Hertzsprung-Russell (HR) diagram of \( \log(L/L_\odot) \) versus \( T_{\text{eff}} \), as shown in Figure 5. We see from this figure that the 270 plotted CATSUP stars all lie along the main sequence, with light scatter possibly due to binaries (see Section 3) or parameter errors. An examination of the spectral types (see Section 5) revealed that <5% of the CATSUP stars are (sub)giants, meaning that the vast majority of these stars are dwarfs. The data in Figure 5 have been color-coded with respect to the stellar activity indicator, \( \log R'_{\text{HK}} \). While we will discuss this more at length in Section 6, we see that low-activity stars scatter brighter luminosities above the main sequence than high-activity stars.

We have plotted a distribution of all the Hypatia stars (dark green) with respect to \([\text{Fe}/\text{H}]\) in Figure 3, where \([\text{Fe}/\text{H}]\) is given in 0.1 dex bins since the typical associated \([\text{Fe}/\text{H}]\) error is \( \pm 0.05 \) dex. From this plot we see that the majority of stars in Hypatia have solar-like \([\text{Fe}/\text{H}]\) content. The \([\text{Fe}/\text{H}]\) distribution of stars within CATSUP is in light green in Figure 3. From the two overlapping samples, we see that the \([\text{Fe}/\text{H}]\) distribution of the CATSUP subsample mirrors that seen in the full Hypatia Catalog, which are strongly centered around the solar value of iron or \([\text{Fe}/\text{H}] = 0.0 \) dex. Within both the 30 pc and 150 pc sample of CATSUP and Hypatia, respectively, there is a relatively similar spread in \([\text{Fe}/\text{H}]\) at all distances, which is likely a homogeneous mixture or similar stellar origin within the solar neighborhood.

### 5. Spectral Types

Historically, spectral types have been useful for pooling stars with similar temperatures and luminosities, identifying spectral anomalies through comparison of spectra to standard stars, estimating effective temperatures, correcting for the effects of interstellar reddening on colors, and estimating distances to stars lacking accurate trigonometric parallaxes. The latter three reasons are generally not important for studying nearby star samples, as the reddening within the Local Bubble is negligible (Reis et al. 2011), and most of the stars studied here have accurate parallaxes (e.g., Anderson & Francis 2012; Gaia Collaboration et al. 2016). The modern grid of MK spectral standard stars is described in Section 4.1 of Pecaut & Mamajek (2016) and Henry et al. (2002). We queried Brian Skiff’s compendium of MK classifications (Stassun et al. 2017) to obtain a fairly complete breakdown of each star’s historical spectral classifications and notes (e.g., peculiarities, binarity, etc.). There were minor shifts in the spectral types of some FGK-standard stars between the 1940s and 1980s by Philip C. Keenan. In the interest of having the spectral types as close to being on the modern MK system as possible (represented by the dwarf standards of Keenan & McNeil 1989 among the FGK-type stars), we preferentially adopted spectral types classified since 1989, especially those published by expert classifiers using CCD spectra (e.g., Gray et al. 2003, 2006).

Classifications from the Michigan Spectral Survey (e.g., Houk & Cowley 1975) are only used where necessary, as their standard star grid varied somewhat from modern grids. This variation sometimes results in systematic offsets at the \( \pm 1.5 \) subtype level, however, these can be corrected following Table 5 of the Pecaut & Mamajek (2016) paper. A total of 6 spectral types for the CATSUP stars were adjusted from the Michigan Spectral Survey and have been annotated with an asterisk next to their references in Table 3. For some subtypes (e.g., K3V), no adjustment was necessary. Fortunately, most nearby bright stars in our survey had CCD spectra classified by the NStars project by Gray et al. (2003) and Gray et al. (2006), based on the modern grid of standards discussed in Section 4.1 of Pecaut & Mamajek (2016). The spectral types for the CATSUP stars, and their respective sources, can be found in Table 3.

### 6. Ca II H and K Indices

A widely utilized measure of stellar activity derivable from ground-based observations has been the amount of chromospheric emission in the cores of the Ca II H and K lines, at 3968 Å and 3933 Å, respectively. One of the most physically meaningful parameterizations of this emission is the \( R'_{\text{HK}} \) index[^10].

### Table 1

A Summary of the Velocity Components of CATSUP Stars with Different Activity Levels

| \( \log R'_{\text{HK}} \) | Very Active \( x > -4.2 \) | Active \(-4.75 < x \leq -4.2 \) | Inactive \(-5.1 < x \leq -4.75 \) | Very Inactive \( x \leq -5.1 \) |
|-----------------|----------------|----------------|----------------|----------------|
| mean \( U \)    | -12.40         | -10.83         | -13.69         | 1.96           |
| std \( U \)     | 22.02          | 29.22          | 42.16          | 41.19          |
| mean \( V \)    | -22.81         | -16.42         | -28.81         | -74.96         |
| std \( V \)     | 17.25          | 18.91          | 29.99          | 48.14          |
| mean \( W \)    | -13.86         | -8.76          | -7.04          | 3.00           |
| std \( W \)     | 13.85          | 13.86          | 23.64          | 13.45          |

[^10]: [http://cds bib.u-strasbg.fr/cgi-bin/cdsbib?2014yCat....1.2023S](http://cds bib.u-strasbg.fr/cgi-bin/cdsbib?2014yCat....1.2023S)
that is defined by Noyes et al. (1984) as being the chromospheric flux in the combined H and K lines radiated by a star relative to the bolometric flux of the star. It is an index that has been corrected for photospheric contributions to the flux across the wavelengths of the H and K lines, which are the chromospheric emissions (reversals) of the Ca II H and K lines. Early discussions of the behavior of this index, or similar ones not corrected for a photospheric component, among nearby late-type dwarf stars can be found in Middelkoop (1982), Hartmann et al. (1984), Noyes et al. (1984), Soderblom (1985), all of whom built on the work of Wilson (1978); Vaughan & Preston (1980).

Values of log $R'_{\text{HK}}$ emission measurements are listed in Table 3, for 627 stars within CATSUP, Table 3. These values were selected from a larger database that was compiled from papers in the literature prior to 2011 by Smith (2011), in addition to two stars from Gomes da Silva et al. (2014). The characteristics of this pre-2011 database of log $R'_{\text{HK}}$ values have been discussed by Smith & Redenbaugh (2010) and Smith (2011), who also describe the manner in which the database was compiled. By far, the largest literature sources used in the compilation of Smith (2011) are the following: Gray et al. (2005, 2006), Henry et al. (1996, 2000, 2008), Noyes et al. (1984), Soderblom (1985); Soderblom et al. (1991), Wright et al. (2004). Where multiple literature values were available, they were averaged with equal weights, after first applying systematic offsets to values from Gray et al. (2005, 2006), in order to yield a homogenized data set. More details are discussed in Smith (2011), whose paper can also be resorted to for a discussion of possible time variability in the H and K emission, as well as references to a number of other smaller literature sources that were used. All of those stars with Ca II H and K indices can also be found in the TESS Input Catalog (Stassun et al. 2017).

An HR diagram for the CATSUP stars for which Ca II H and K emission has been measured is shown in Figure 5, where the data points have been coded on a continuous color-scale according to the value of the log $R'_{\text{HK}}$ emission parameter. This figure illustrates the main sequence nature of the majority of the CATSUP stars. There are some more-evolved stars that scatter by up to $\sim 0.5$ dex in log $(L/L_\odot)$ above the main sequence. Among solar-type dwarfs with $T_{\text{eff}} > 5400$ K these more-evolved...
stars tend to exhibit relatively low levels of Ca II H and K emission $\log R'_{\text{HK}} < -4.8$. Relatively few dwarfs cooler than 5400 K in Figure 5 are found to have such low levels of activity. Consequently, the values of $-4.8 < \log R'_{\text{HK}} < -4.5$ that do dominate among the more-evolved CATSUP stars in the solar-like temperature regime can be considered closer to the lower levels of activity encountered in the cooler CATSUP stars. Wright et al. (2004) found that many so-called “Maunder Minimum” stars of near-solar temperature but of notably lower activity levels than the average Sun, are in fact slightly evolved from the main sequence. The distribution of CATSUP stars with $\log R'_{\text{HK}} < -4.9$ seems consistent with the findings in Wright et al. (2004).

The distribution of chromospheric activity within the CATSUP sample is shown in Figure 6. The pioneering work of Vaughan & Preston (1980) indicated a bimodal distribution among nearby dwarf stars, with high-activity and low-activity groups being separated by the so-called Vaughan–Preston gap. This gap can also be seen in the samples discussed by Middelkoop (1982); Noyes et al. (1984); Soderblom (1985). A bimodality was evinced in the $R'_{\text{HK}}$ surveys of Henry et al. (1996) and Gray et al. (2006). The survey of southern hemisphere stars by Jenkins et al. (2008) found that the gap corresponded to a relatively low percentage of stars with activity levels of $\log R'_{\text{HK}} \sim -4.7$, while active and inactive stars had mean levels of $-4.5$ and $-5.0$, respectively. While a corresponding low activity peak at $\log R'_{\text{HK}} \sim -4.9$ is seen for the CATSUP distribution in Figure 6, a possible high activity peak near $\sim -4.4$ is quite muted. Within the CATSUP sample the Vaughan–Preston gap does seem to be relatively well populated, with a broad continuous distribution extending across the activity range from $-4.8$ to $-4.3$.

Gray et al. (2006) found that the distribution of $\log R'_{\text{HK}}$ differs between stars of different metallicities, with a bimodality largely being confined to dwarfs with $[\text{M/H}] > -0.2$ dex. Within Figure 6 we have similarly divided the CATSUP sample into metallicity groupings of $[\text{Fe/H}]$ less than or greater than $-0.2$ dex. The more metal-rich bin within CATSUP is not as strikingly bimodal as that shown in Figure 5 of Gray et al. (2006), while the metal-poorer distribution in our Figure 6 is similar to that found in their Figure 5. Stars above the Vaughan–Preston gap are thus largely of metallicities similar to the Sun, while dwarfs with $[\text{Fe/H}] < -0.2$ dex constitute a significant component of the low activity peak.

### 7. UV Photometry with GALEX

An additional stellar activity measure critical to the understanding of exoplanets is the UV light from host stars. As the high-energy UV photons alter the planets’ atmospheric evolution and photochemistry, interpretations of exoplanetary spectra are affected for both close-in giant planets and habitable zone Earths (Miguel & Kaltenegger 2014; Luger & Barnes 2015; Rugheimer et al. 2015; Arney et al. 2016). We cross-correlated the CATSUP target catalog with the archived UV photometry of the GALEX space mission from the General Release

The NUV detector in 2009 resulted in only NUV imaging for all observations after this date. We queried the GALEX archive for all stars in the catalog using a search radius of 30″.

The NUV detector response becomes nonlinear beyond 34 counts per second, which occurred for 102 (11%) of the CATSUP targets. In the case of nonlinearity for these NUV measurements, we report the pipeline’s measured flux density as a lower limit, and Shkolnik (2013) was used as a reference for upper limits for bright targets in GALEX. In the FUV, the detector’s response becomes nonlinear beyond 108 counts per second, but only affected a tiny fraction of the CATSUP stars. GALEX did not detect 309 (32%) of the stars in the FUV for which we report estimated upper limits. Flux densities, including their upper limits in the case of non-detection and lower limits in the case of nonlinear detector response, are listed in Table 3. If a star’s NUV or FUV emission was detected by GALEX, but it was unable to be measured

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Figure 5. Hertzsprung-Russell diagram of 270 CATSUP stars, where stars are color-coded according to $\log R'_{\text{HK}}$ emission measurements of stellar activity. This figure was made using Filtergraph (Burger et al. 2013).

Figure 6. Frequency distribution of the CATSUP stars with respect to $\log R'_{\text{HK}}$ for two populations of stars, one with $[\text{Fe/H}] > -0.2$ dex and one with $[\text{Fe/H}] < -0.2$ dex. Both distributions are shown with 0.05 bins of $\log R'_{\text{HK}}$ in keeping with Gray et al. (2006), Henry et al. (1996), and Jenkins et al. (2011).

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The GALEX GR6/7 is available at http://mastweb.stsci.edu/gcasjobs/.
completely due to a limited field of view, the data were deemed unreliable and excluded from the final catalog. There are 708 stars with UV measurements within CATSUP, and 676 of those stars can also be found in the TESS Input Catalog (Stassun et al. 2017).

In Figure 7, we show a plot of the effective temperature ($T_{\text{eff}}$) with respect to the logged fluxes for both the FUV (blue) and NUV (red) with individual error bars. When $T_{\text{eff}}$ is below 5500 K, the FUV scatters due to the interference with the star’s chromosphere, namely that coronal interference is higher than the blackbody curve. Above $T_{\text{eff}} = 5500$ K, the FUV flux is dominated by the photosphere, which is temperature-dependent. As the photosphere becomes a smaller fraction of the total FUV bandpass, the flux is increasingly from the chromosphere, the transition region, and the corona, which is dominated by stellar activity and not effective temperature. The NUV is only well detected when $T_{\text{eff}} < 5200$ K, hence the sharp cutoff for the red data points. This temperature cutoff also affects the number of data points in the $[f_{\text{FUV}}/f_{\text{NUV}}]$ relation, or the ratio of the flux densities in FUV and NUV bandpasses in GALEX, shown on the right in Figure 7. The trend toward higher ratios with smaller effective temperature is due to the rapid reduction in NUV photons from the stellar photosphere. The large range in the UV ratio at a given temperature is due to variations in stellar activity. Per Figure 7, we note that ~10 stars have $T_{\text{eff}} < 3900$ K, the typical cutoff between K and M dwarfs. We have confirmed that their effective temperatures are accurate, such that in nearly all cases, these stars were measured by multiple sources that gave similar temperatures. Since there are no obvious reasons for excluding these stars, we have opted to keep them within CATSUP.

Smith & Redenbaugh (2010) and Findeisen et al. (2011) showed that the GALEX FUV magnitude of FGK dwarfs was sensitive to the level of stellar activity as judged from the strength of the Ca II H and K emission lines. The CATSUP stars also verify this result. Figure 8 presents a two-color $B$–$V$ diagram for CATSUP stars for which GALEX measurements of FUV magnitude have been made. It shows a hybrid color denoted FUV–$V$, which is obtained by combining the GALEX FUV magnitude and Johnson $V$ magnitude (following the precepts of Findeisen et al. 2011), plotted against Johnson $B$–$V$ color. To bring out the variation of FUV brightness with stellar activity, the data points have been color-coded according to the categories defined by Henry et al. (1996). There are few stars in the very inactive category, but the other three activity categories are well represented and have clear differences in the FUV–$V$ color at a given $B$–$V$.
the FUV–V color decrease due to increasing flux in the GALEX FUV band arising from stellar active regions. Interested readers are referred to the papers by Smith & Redenbaugh (2010) and Findeisen et al. (2011) for much more detail about this trend.

8. X-ray Data

X-ray fluxes, luminosities, and fractional luminosities were based on observations with the Chandra, XMM, and ROSAT missions. The derived X-ray fluxes were converted to a common energy band (ROSAT) to facilitate intercomparison of the various X-ray indices. Additionally, ROSAT was used as a baseline since much previous work explored rotation-activity relations and age dating using X-ray luminosities from that mission (Mamajek & Hillenbrand 2008; Wright et al. 2011).

8.1. Chandra

The Chandra X-ray Observatory provides X-ray imaging in peak energy range ~0.5–7.0 keV, with a sub-arcsecond point-spread function, over a ~60–250 arcmin² field of view (Weisskopf et al. 2000). We initially queried the CATSUP catalog (J2000 positions from SIMBAD) against the Chandra Source Catalog, Release 1.1 (Evans et al. 2010, 2014), which cataloged X-ray sources in imagery from the Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003). Chandra positions have an astrometric accuracy better than ~1″,12 and broadband fluxes (“b”) in the 0.5–7.0 keV were recorded. Vetting of the Chandra X-ray counterparts against the optical astrometry yielded 11 reliable matches.

8.2. XMM

The X-ray Multi-Mirror Mission (XMM-Newton) European Photon Imaging Camera (EPIC) (Strüder et al. 2001) has a field of view of 30’ and covers the energy range 0.15–15 keV with moderate angular resolution (~6″). A query of the CATSUP database (J2000 SIMBAD positions) with the 3XMM-DR5 catalog of serendipitously detected X-ray sources (Rosen et al. 2016) yielded 54 X-ray sources within 90°. To ease comparison with the ROSAT X-ray fluxes, the XMM fluxes in bands 1, 2, and 3 were added, covering 0.2–2.0 keV.

8.3. ROSAT

ROSAT (ROentgen SATellite) conducted the ROSAT All-Sky Survey (RASS Voges et al. 1999, 2000) during a half-year period shortly after launch in 1990. The RASS mapped 99.7% of the sky with exposure times over 50 s in the 0.1–2.4 keV band with the Position Sensitive Proportional Counter (PSPC), and cataloged 18,811 sources down to an approximate limiting count rate of 0.05 cts s⁻¹ (Voges et al. 1999) in the Bright Source Catalog (RASS-BSC; 1RXS). The faint star extension of the RASS was published as the Faint Source Catalog (RASS-FSC) of 105,924 X-ray sources (Voges et al. 2000). A re-analysis of the RASS was recently completed by Boller et al. (2016), and resulted in a catalog of 135,000 X-ray sources in the 2nd ROSAT All-Sky Survey source catalog (2RXS). Until the future eROSITA mission completes its survey, the 2RXS provides the astronomical community with the deepest all-sky X-ray survey. We adopted the count rates and hardness ratio (HR1) from Boller et al. (2016) to calculate the energy conversion factor and resultant X-ray flux in the 0.1–2.4 keV band using the linear trend from Fleming et al. (1995):

$$E F = (8.31 + 5.30 \text{ HR1}) \times 10^{-12} \text{ erg cm}^{-2} \text{ ct}^{-1}. \quad (1)$$

Both the original RASS analyses and the revised RASS catalog produced by Boller et al. have similar positional uncertainties of typically ~13″ (Boller et al. 2016). Experience has shown that an optimal search radius for matching optical stars with their RASS X-ray counterparts is 40″ (Neuhaeuser et al. 1995). A larger search radius of 90″ was employed in a few cases to retrieve matches for some of the nearest stars that had large proper motions.

The Second ROSAT PSPC Catalog (Rosat 2000) of X-ray sources detected in pointed PSPC observations was also queried with both 40″ and 90″ search radii around the positions of the CATSUP stars. A total of 109 stars had X-ray sources present in both the ROSAT All-Sky Survey and the Second ROSAT PSPC Catalog. As the pointed observations in the latter catalog had longer exposure times than those in the All-Sky Survey, we adopted the PSPC count rates and hardness ratios HR1 from the latter, and calculated soft X-ray fluxes using the previously mentioned formula from Fleming et al. (1995).

8.4. X-Ray Flux Conversion

We would like the X-ray fluxes to be on a common system so that stellar activity levels can be usefully compared between stars. Comparison of the XMM, Chandra, and ROSAT fluxes among sources with detections in multiple surveys produced plots with large scatter (likely due to X-ray variability) and it was not clear that empirical flux conversions could be accurately estimated. We decided to use the WebPIMMS tool, or Portable, Interactive Multi-Mission Simulator13 (Mukai & Shiokawa 1993), to intercompare the X-ray fluxes between the observatories. For calculating X-ray flux conversions, we required an estimate of the H I column density. The median distance to the stars in the CATSUP catalog (d < 30 pc) is ~24 pc. Trends of hydrogen column density versus distance within the Local Bubble are consistent with neutral hydrogen densities of $n_{\text{HI}} = 0.1 \text{ cm}^{-3}$ (Linsky et al. 2000). Hence, for a mean distance of 24 pc for our sample stars, we adopt log N (H I) = 18.8 as a representative hydrogen column density for the CATSUP sample for the webPIMMS tool.

The conversion between X-ray fluxes for one instrument and another depends on the temperature of the plasma, its chemical composition, and the intervening hydrogen column. Johnstone & Güdel (2015) demonstrated a strong correlation between coronal X-ray temperature and X-ray surface flux for main sequence stars with masses between ~0.2 and ~1.1 $M_\odot$:

$$T_{\text{cor}} = 0.11 F_{\text{X}}^{0.26}. \quad (2)$$

The correlation spanned inactive stars, such as the Sun at solar, minimum ($T_X \approx 1.0 \text{ MK}, F_X \approx 10^{3.65} \text{ erg s}^{-1} \text{ cm}^{-2}$), to very active stars like 47 Cas B ($T_X \approx 11 \text{ MK}, F_X \approx 10^{7.61} \text{ erg s}^{-1} \text{ cm}^{-2}$). Indeed coronal temperatures scale much more closely with X-ray surface flux than with X-ray luminosity ($L_X$) or with the X-ray-to-bolometric luminosity ratio ($R_X = L_X/L_{\text{bol}}$). To produce self-consistent X-ray flux conversions between the XMM, Chandra and ROSAT data, we iteratively solve for a consistent combination of $F_X$ and $T_{\text{cor}}$ using the Johnstone & Güdel (2015) power law. An initial estimate of $T_{\text{cor}}$ is adopted (1 MK), and an initial conversion from Chandra or XMM X-ray flux to ROSAT flux

12 http://cxc.harvard.edu/cal/ASPECT/celmon/

13 heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl
is calculated using PIMMS at this temperature (adopting $\log N (\text{H} I) = 18.8$ and solar composition). Then, an initial X-ray surface flux ($F_X$) is calculated, and a revised coronal temperature $T_{\text{cor}}$ is recalculated. This cycle is iterated until $T_{\text{cor}}$ changes by less than 0.01 dex between iterations. The iterative method encountered a few troublesome cases for low $T_{\text{cor}}$ that would not converge, all with $T_{\text{cor}} < 1$ MK. Based on the observed X-ray fluxes at solar minimum and that observed for coronal holes, we simply adopted $T_{\text{cor}} = 1$ MK for these cases.

The final converted fluxes, flux errors, luminosity, and activity from the XMM, Chandra, and ROSAT X-ray missions can be found in Table 3. A total of 364 stars have X-ray measurements within CATSUP, and 363 of those stars can also be found in the TESS Input Catalog (Stassun et al. 2017). A plot of the fractional X-ray luminosity $\log R_x = \log (L_x / L_{\text{bol}})$, using the median value of $\log R_x$ from the three missions, with respect to $T_{\text{eff}}$ is shown in Figure 9. The yellow line is the coronal activity value of the Sun, while the green line is the empirical X-ray saturation limit using the median value of $\log N (\text{H} I) = 18.8$ and solar composition per Wright et al. (2011). The two lines show that the majority of the CATSUP stars (with X-ray measurements) fall within these two values and that the upper envelope is relatively constant across spectral types, which implies saturation. We also see that the cooler, lower-mass stars are more active. The spread in the $\log R_x$ values is likely the result of different rotation rates, since it is expected that equal-mass stars would have approximately the same bolometric luminosity.

As a consistency check, we searched Table 3 for stars with X-ray measurements from two different instruments, in order to compare their normalized fluxes. Among our sample, we find 22 stars with both ROSAT and XMM data, and three stars with both ROSAT and Chandra measurements. The derived flux values are plotted relative to one another in Figure 10. For all points, the abscissa is the normalized flux from ROSAT, and the ordinate can be either flux from XMM (filled green) or Chandra (empty blue). The flux values generally show good agreement for the X-ray-brighter stars, suggesting that our normalization process is reliable when the fluxes are well measured. At the dimmer end, some stars deviate from the one-to-one line, a likely consequence of poorer counting statistics in the shallower ROSAT survey. However, intrinsic fluctuations in the X-ray brightness such as, for example, those due to solar-type cycles, could also contribute.

9. Application

The CATSUP data set combines a variety of properties for stars within 30 pc, such that individual stars as well as the solar neighborhood can be better characterized. To take advantage of the assorted available properties, we have plotted the Ca II H and K emission index $\log R'_{HK}$ with respect to both $B$–$V$ colors in Figure 11. We have color-coded the stars to show the likely disk component of origin, where orange is a thin disk and blue is a thick disk, based on their kinematics per Bensby et al. (2003) and Hinkel et al. (2014). The thick-disk stars are mainly concentrated around $\log R'_{HK}$ of $\sim-5.0 \pm 0.2$. In other words, they have emission indices comparable to the Sun—they are mostly very low-activity. Along these lines, we considered whether the heights above/below the Galactic plane ($Z$) and...
[Fe/H] correlate with a stellar activity index (that is sensitive to age). We did not see any trends with respect to log \( R'_{\text{HK}} \) versus [Z], or with respect to a multitude of abundances within both thin-disk and thick-disk stars; see Figure 12. The conclusion that we can draw is that CATSUP stars encompass the full range of Z-height values in both the thin-disk and thick-disk subsets, regardless of their level of Ca\( \text{II} \) H and K stellar activity indices (at least for \( \log R'_{\text{HK}} < -4.8 \) or so).

The thick-disk stars typically have \( \log R'_{\text{HK}} < -4.8 \), and thus fall in the low-activity grouping below the Vaughan–Preston gap (Vaughan & Preston 1980) in plots of Ca\( \text{II} \) H and K activity versus \( B-V \). As such, the thick-disk stars populate the peak at \( \log R'_{\text{HK}} \sim -4.9 \) in Figure 6. If the thick-disk stars are removed from the histogram in Figure 6, the resulting distribution for thin-disk stars still shows a pronounced local maximum near \(-4.9\). Thus, a high incidence of inactive stars is a property of the thin disk as well as the thick disk.

Looking at the two populations of stars in Figure 11, there are 536 stars from the thin disk, while 43 are from the thick disk (\( \sim 8\% \)). To better understand these two stellar populations, we utilize a two-sample Kolmogorov–Smirnov (KS) test that analyzes whether the two samples are drawn from the same distribution. If the \( p \)-value is below a certain significance level, typically 0.05, then the null hypothesis (that the two samples are from the same distribution) is rejected. Note that the \( p \)-value is not the probability of the null hypothesis being true or false. In other words, a \( p \)-value >0.05 does not mean that the two samples are similar; it merely states that there was no evidence to show that the two samples were significantly different. This point is subtle and often misinterpreted within the literature. A two-sample KS test of the log \( R'_{\text{HK}} \) values for thin-disk and thick-disk stars yields a \( p \)-value = 2.02 \times 10^{-7}—meaning that the two samples are statistically different.

We see in Figure 11 that thick-disk stars have predominantly low values of log \( R'_{\text{HK}} \), typically log \( R'_{\text{HK}} < -4.8 \). For all stars with log \( R'_{\text{HK}} < -4.8 \), there are 233 stars from the thin disk and 35 from the thick disk (\( \sim 15\% \)). Doing a two-sample KS test on the log \( R'_{\text{HK}} \) values for thin-disk and thick-disk stars where log \( R'_{\text{HK}} < -4.8 \) gives \( p = 0.006 \). Finally, we did a two-sample KS test for the log \( R'_{\text{HK}} \) values for those stars in the thick disk and with log \( R'_{\text{HK}} < -4.8 \) (total 35 stars) with respect to the entire sample of thin-disk stars (total 536 stars)—the \( p \)-value is 2.82 \times 10^{-11}.

Vaughan & Preston (1980) searched for kinematic differences among some 185 dwarfs with different levels of Ca\( \text{II} \) H and K activity. They found that for dwarfs of a given spectral type, groupings according to strong H and K emission (high activity) have smaller dispersions in the component of space motion perpendicular to the Galactic plane. Thus, the chromospherically younger stars in their sample have different mean space motions than chromospherically older stars. Soderblom (1990) extended this work with a larger sample of chromospherically active solar-like, K, and M dwarfs, finding them to have kinematics consistent with a young population with ages around 0.5–2 Gyr. The age dependence of space motion provides a tool for studying the dynamical evolution of the Galactic disk (e.g., Wielen 1974). As such, any correlations between stellar kinematics and stellar activity are worth searching for among the CATSUP stars. Jenkins et al. (2011) have published a very thorough study of the correlations for solar-type dwarfs and subgiants, highlighting the utility of this approach.

The distributions of the \( (U, V, W) \) components of space motion of the CATSUP stars are shown in Figure 13, with some summary characteristics listed in Table 1. In the table, the CATSUP stars have been divided into the four stellar activity groupings defined by Henry et al. (1996), as also adopted in Section 7, and for each grouping the mean value of each velocity component is listed along with the standard deviation. We leave the “very inactive” stars out of the discussion because of their small number within the CATSUP sample. In terms of the \( W \) component of velocity perpendicular to the Galactic plane, the velocity dispersion among the inactive stars is notably greater than that among the active and very active dwarfs. This is also the case for the standard deviations in the \( U \) and \( V \) components of motion. Thus, overall the inactive stars evince a greater dispersion in all three velocity components than the active stars. This trend is partly but not entirely driven by the thick-disk dwarfs within CATSUP. Inspection of Figure 13 shows that these trends exist even within the thin disk population alone. The upper panels of Figure 13 illustrate the offsets in mean \( U \) and \( V \) velocity between the thick-disk and

![Figure 12](image-url)  
Figure 12. Stellar activity with respect to the absolute Z-heights above the plane for [Fe/H], where stars in the thin disk are shown on the left, while stars in the thick disk are on the right.
thin-disk stars. Thus, the CATSUP sample verifies and extends the early results of Vaughan & Preston (1980), and is consistent with the findings of Soderblom (1990) and Jenkins et al. (2011; see their Figure 16, which our Figure 13 is analogous to).

Ultimately, it seems that the thick-disk stars predominantly have low activity, and higher velocity dispersions on average toward or away from the Galactic plane. The CATSUP set of thick-disk stars has a distinctly different distribution of chromospheric activity than the CATSUP thin-disk stars. We note as a caveat, however, that the number of thick-disk stars in our sample is roughly an order of magnitude smaller than the number of thin-disk stars.

10. Summary

We have assembled a data set of stellar properties for 951 FGK-type stars within 30 pc of the Sun. Beginning with the Gaia TGAS subset of astrometric data, we have combined information regarding multiplicity within stellar systems (ExoCat), stellar abundance measurements (Hypatia), standardized spectral types, Ca II H and K stellar activity indices, NUV and FUV photometry from GALEX, and X-ray fluxes and luminosities from ROSAT, XMM, and Chandra. The aim of this project was to collate a wide variety of data for nearby stars such that they could be more easily characterized. The information available in CATSUP can be utilized for the direct sample or act as a proxy for similar stars, in order to better understand the overall trends within solar neighborhood stars, as well as stars that host exoplanets. CATSUP was compiled in anticipation of upcoming exoplanet surveys such as TESS, CHEOPS, and WFIRST.

While we included data currently available within the literature, we also presented new stellar information. We explored the GALEX UV data and found that the FUV and NUV flux correlated strongly with effective temperature, as the photospheres of hotter stars have bluer peaks in their Planck functions. At temperatures below 5500 K, the data show a much larger range at a given $T_{\text{eff}}$, due to higher contributions to the FUV emission from the more variable stellar corona and a high chromosphere compared with hotter stars (see Figure 7, left). At higher temperatures, the FUV flux is more linear with $T_{\text{eff}}$ since it is dominated by the temperature-dependent stellar photosphere. In general, the NUV data show a larger range at a given effective temperature. When combined into a flux density ratio in the FUV and NUV bandpasses per Figure 7 (right), the influence of the stellar corona/transition region/chromosphere

Figure 13. The chromospheric activity indicator $\log R_{\text{HK}}$, based on the Ca II H and K emission lines, is plotted vs. the $U$, $V$, and $W$ velocity components of space motion, as well as the total space velocity for stars in the CATSUP sample. Thick-disk stars are depicted with filled symbols, and thin-disk stars are plotted with open circles. The four stellar activity groupings defined by Henry et al. (1996) are indicated by the horizontal dashed lines and labeled accordingly.
over the photosphere at low temperatures is again present. Additionally, we analyzed how $R_{\log HK}$ activity affected stellar spectral energy distributions, such that more active stars had bluer FUV–V colors.

X-ray data from multiple missions were combined per a new methodology that allowed all available X-ray information to be utilized for stellar characterization. The X-ray data were investigated with respect to effective temperature in Figure 9. The majority of the stars were found to fall between the solar coronal activity and the X-ray saturation limit, where the latter was exemplified by a relatively constant $R_{\log x}$ across spectral types. Overall, the smaller, cooler stars were found to have the highest fractional X-ray luminosity or coronal activity indicators. We compared the coronal activity ($R_{\log}$) and chromospheric activity ($R_{\log HK}$) in the same manner as Mamajek & Hillenbrand (2008); see Figure 14. We found a similar correlation with respect to a linear trend, where the overlaid line is defined as $y = 0.28687x - 3.1668$, and range in data.

Finally, we examined the correlation between stars in the CATSUP sample that are likely to have originated from the thick disk (see Section 4) and the Ca II H and K index $R_{\log HK}$. We found that the thick-disk stars had chromospheric activity that was preferentially $R_{\log HK} < -4.8$ in Fig 11. Compared with the thin-disk stars, these kinematic stellar sub-groups within CATSUP were statistically different per a two-sample KS test. When analyzing $R_{\log HK}$ with respect to UVW galactic velocity, the lower-activity stars had greater dispersion in the three individual galactic velocity components, a trend that is not wholly attributable to the presence of thick-disk stars.

While there are a number of additional trends to be found between the 951 CATSUP stars, we leave this task to future papers either by the ASU NExSS team or by other colleagues. The properties within CATSUP were strategically combined in order to maximize characterization of nearby main sequence stars. It is our goal that by knowing more about stars from both a physical and chemical perspective, we will enable a greater understanding of the solar neighborhood. Additionally, we hope that CATSUP will help inform either target selection or follow-up observations for the TESS, CHEOPS, andWFIRST missions.

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Appendix

In this section we present supplementary information for use along with the main manuscript. In Table 2, we provide a description of the new catalogs added into Hypatia per the 2.1 update, similar to those tables given in Hinkel et al. 2014, 2016. In Table 3, we give a description of the columns, data, and units within CATSUP, where the data can be downloaded online either via ApJ or Vizier.
| Catalog       | Telescope                                                                 | Resolution | S/N   | \(\lambda\) Range | Stellar Eq. | CoG or SPECTRUM | Solar | Num. of Fe i/ii Lines |
|---------------|----------------------------------------------------------------------------|------------|-------|---------------------|-------------|------------------|-------|----------------------|
| Adibekyan et al. (2016) | HARPS (3.6 m ESO telescope, La Silla, Chile) and UVES (8 m VLT/UT2 telescope, La Silla, Chile) | 200–2300   |       | 4000–65000          |            |                  |       | 250/40               |
| Battistini & Bensby (2016) | FEROS on the ESO 1.5 m and 2.2 m telescopes and MIKE on the Magellan Clay telescope; UVES on the ESO Very Large Telescope | >200      | 3500–9500 |            |            | IRAF splot       |       | 226/36              |
| Baumann et al. (2010)     | Robert G. Tull coude spectrograph on the 2.7 m Harlan Smith telescope; MIKE spectrograph on the 6.5 m Magellan Clay telescope; HARPS spectrograph on the 3.6 m ESO telescope | >200      | 4500–7800/3350–9500/4445–8294 |            |            | IRAF splot       |       | 34/11               |
| Brewer et al. (2016)      | HIRES spectrograph at the Keck I Telescope                                 | >200       | 5164–7800 |            |            | spectral fitting |       | 600/300             |
| Chen et al. (2001)        | 2.16 m telescope at Beijing Astronomical Observatory (BAO) with the Coude Echelle Spectrograph (CES) | >150       | 5500–9000 |            |            | IRAF splot       |       | 142/8               |
| da Silva et al. (2015)    | Observatorio de Haute-Provence (OHP) using the ELODIE spectrograph       | >200       | 3895–6815 |            |            | IRAF splot       |       | 72/12               |
| Delgado Mena et al. (2014, 2015) | HARPS at 3.6 m ESO La Silla Observatory (Chile); UVES at 8.2 m Kueyen UT2 (VLT); FEROS at 2.2 m ESO/MPI telescope; SARG 3.5 m TNG; FIES at 2.6 m Nordic Optical Telescope; SOPHIE at 1.93 m OHP; CORALIE at 1.2 m Euler Swiss telescope; and UES at 4.2 m William Herschel Telescope | 100000/115000/48000/57000–86000/67000/75000/50000/55000 | 55% of the spectra >200 | 3800–7000/3000–4800/4800–6800/3600–9200/5100–10100/3700–7300/3820–6930/3800–6800/4600–7800 | IRAF splot | MOOG2010 per Sneden (2013) |       | N/A 137/287         |
| Gonzalez et al. (2001, 2010a, 2010b) | 2.7 m telescope at McDonald using the 2dcoude spectrometer and 4 m Blanco Telescope at Cerro Tololo Inter-American Observatory (CTIO) | >59000/35000 | 195–620 | 3700–10000/5850–8950 | IRAF splot |            | MOOG per Sneden (2013) |       | their own 64/11     |
| Gonzalez (2014, 2015)     | McDonald Observatory 2.1 m Otto Struve telescope and Sandiford spectrograph | 53000      | 300–350 |            |            | IRAF splot       |       | 45–55/6–8           |
| Ghezzi et al. (2010)      | FEROS on the MPG/ESO-2.20 m telescope                                      | >200       | 3560–9200 |            |            | IRAF splot       |       | 27/12               |

Table 2
Hypatia 2.1 Update
| Catalog               | Telescope                                      | Resolution        | S/N   | λ Range    | Stellar Eq. | CoG or SF Scale | Solar Scale | Num. of Fe I/II lines | Stars in Hypatia |
|-----------------------|-----------------------------------------------|-------------------|-------|------------|-------------|-----------------|-------------|-----------------------|-----------------|
| Israeli et al. (2004, 2009) | 4.2 m WHT/UES (La Palma); the 3.5 m TNG/SARG (La Palma); the 1.52 m ESO (La Silla) and the 1.2 m Swiss/CORALIE (La Silla) | 55000/57000/50000/50000 | 150–350 | 3800–6800 | ATLAS9 per Kurucz (1993) | IRAF plot | MOOG per Sneden (1973) | Anders & Grevesse (1989) |
| Lambert et al. (1991)  | W. J. McDonald Observatory with the 2.7 m telescope | >150              |       |            | ATLAS per Kurucz (1993) | Uppsala EQWIDTH | Uppsala EQWIDTH | Anders & Grevesse (1989) |
| Lambert & Reddy (2004) | 2.7 m telescope at McDonald using the 2dcoode spectrometer | 60000          | 100–200 | 3500–9000 | ATLAS9 per Kurucz (1993) | IRAF plot | MOOG per Sneden (1973) | Reddy et al. (2003) differential analysis |
| Liu et al. (2014)      | High Dispersion Echelle Spectrograph at Okayama Astrophysical Observatory (OAO); which was equipped at the coude focus of the 1.88 m telescope | 67000          | >200   | 5000–6200; 4000–7540 | MAFAGS spectral synthesis with IDL/ Fortran SIU software (Reetz 1991) | spectral fitting | spectral fitting | their own off Vesta |
| López-Valdivia et al. (2017) | 2.1 m telescope of the Astrofisico Guillermo Haro, located in Mexico, using the Cananea High-resolution Spectrograph (CanHiS) | 80000          | 100    | centered at 5005, 5890, 6310 and 6710 Å | ATLAS12 per Kurucz (1993) | spectral fitting | spectral fitting | their own off Vesta |
| Luck & Heiter (2006)   | 2.1 m telescope at McDonald using the CASPEC | 60000          | >150   | 4840–7000 | MARCS per (Gustafsson et al. 1975) 75 | spectral fitting | spectral fitting | differential analysis |
| Luck & Heiter (2007)   | 2.1 m telescope at McDonald using the CASPEC | 60000          | >150   | 4840–7000 | MARCS per (Gustafsson et al. 1975) 75 | spectral fitting | spectral fitting | differential analysis |
| Luck (2015, 2017)      | McDonald Observatory using the 2.1 m Struve Telescope and the Sandford Cassegrain Echelle Spectrograph | 60000          | >150   | 4840–7000 | MARCS per (Gustafsson et al. 1975) 75 | spectral fitting | spectral fitting | differential analysis |
| Mahdi et al. (2016)    | ELODIE was on the 1.93 m telescope at Observatoire de Haute-Provence (OHP) | 42000          | >70    | 4000–6800 | MARCS per (Gustafsson et al. 1975) | spectral fitting | spectral fitting | differential analysis |
| Maldonado et al. (2015); Maldonado & Villaver (2016) | HERMES spectrograph at the MER-CATOR (1.2 m) telescope at La Palma observatory and FIES at the Nordic Optical Telescope (2.56 m) coude echele spectrograph at the 102 cm telescope at the Vainu Bappu Observatory at Kavalur | 85000/67000/75–480 | 3800–9000 | ATLAS9 per Kurucz (1993) | MARCS per (Gustafsson et al. 1975) | spectral fitting | spectral fitting | differential analysis |
| Mallik et al. (2003)   | coude echele spectrograph at the 102 cm telescope at the Vainu Bappu Observatory at Kavalur | 42000          | 100–350 | 3850–6800 | MARCS per (Gustafsson et al. 1975) | spectral fitting | spectral fitting | differential analysis |
| Mishenina et al. (2012) | 1.93 m telescope at OHP using ELODIE | 42000          | 100–350 | 4400–6800 | ATLAS9 per Kurucz (1993) | MARCS per (Gustafsson et al. 1975) | spectral fitting | differential analysis |
| Mishenina et al. (2016) | 1.93 m telescope at OHP using ELODIE | 42000          | 100–350 | 4400–6800 | ATLAS9 per Kurucz (1993) | MARCS per (Gustafsson et al. 1975) | spectral fitting | differential analysis |
| Catalog       | Telescope                                      | Resolution | S/N       | λ Range     | Stellar     | Eq.          | CoG or       | Solar       | Num. of Fe I/II lines | Stars in Hypatia |
|--------------|-----------------------------------|-------------|-----------|-------------|-------------|--------------|--------------|-------------|----------------------|------------------|
| Nissen (2013)| HARPS at 3.6 m ESO La Silla Observatory (Chile); FEROS at 2.2 m ESO/ MPI telescope | 115000/48000 | 250–1000/200–300 | 3800–6900/3500–9200 | MARCS per (Gustafsson et al. 1975) | IRAF splot | Uppsala EQWIDTH | differential analysis | N/A | 33 |
| Nissen (2016)| HARPS (3.6 m ESO telescope, La Silla, Chile) | 115000 | >600 | 3800–6900 | MARCS per (Gustafsson et al. 1975) | IRAF splot | Uppsala EQWIDTH | differential analysis | 47/9 |
| Notsu et al. (2017)| High Dispersion Echelle Spectrograph attached at the 1.88 m reflector of Okayama Astrophysical Observatory (OAO) | 59000 | 5600–9100 and 4300–7700 | ATLAS9 per Kurucz (1993) | WIDTH9 per (Kurucz 1993) | SPSHOW (in the SPTOOL software developed by Y. Takeda; unpublished) | Anders & Grevesse (1989) | 160/20 | 36 |
| Pagano et al. (2017)| Magellan Inamori Kyocera Echelle (MIKE) spectrograph on the 6.5 meter Magellan II telescope | 50000 | 150–300 | 4700–7100 | ATLAS9 per Kurucz (1993) | ARES/IRAF SPLOT | MOOG14 per Sneden (1973) | Asplund et al. (2009) | 69/14 | 508 |
| Ramírez et al. (2012)| Tull coude spectrograph on the 2.7 m Harlan J. Smith Telescope at McDonald Observatory; MIKE spectrograph on the 6.5 m telescope at Las Campanas Observatory | 60000 (both) | >200 | N/A | MARCS per (Gustafsson et al. 1975) | IRAF splot | MOOG per Sneden (1973) | differential analysis | N/A | 514 |
| Ramírez et al. (2013)| TS2/McD (R. G. Tull Coude spectrograph; 2.7 m Telescope at McDonald Observatory; HRS/HET (High Resolution Spectrograph; 9.2 m Hobby-Eberly Telescope); UVES/VLT (UV-Visual Echelle Spectrograph; 8 m Very Large Telescope); and FEROS/ESO (Fiber-feb Extended Range Optical Spectrograph; ESO 1.52 m Telescope) | 60000/120000/80000/45000 | >100 | ATLAS9 per Kurucz (1993) | IRAF splot | MOOG per Sneden (1973) | differential analysis | 794 |
| Suárez-Andrés et al. (2016)| 3.6 m telescope at ESO equipped with High Accuracy Radial Velocity Planet Searcher (HARPS) using CORALIE | 110000 | 70–2000 | 3800–6900 | ATLAS9 per Kurucz (1993) | ARES | MOOG per Sneden (1973) | Anders & Grevesse (1989) | 263/36 | 1077 |
| Takeda & Kawanomoto (2005); Takeda et al. (2010)| 1.88 m telescope at Okayama Astrophysical Observatory (OAO) using the High Dispersion Echelle Spectrograph (HIDES) | 70000 | 200 | 5800–7000 | ATLAS9 per Kurucz (1993) | WIDTH9 per (Kurucz 1993) | SPSHOW (in the SPTOOL software developed by Y. Takeda; unpublished) | Anders & Grevesse (1989) | 160/20 | 93/83 |
| Trevisan & Barbuy (2014)| 1.52 m telescope at ESO using FEROS | 48000 | 100 | 3560–9200 | MARCS per (Gustafsson et al. 1975) | ARES | ABON2 via Spite 1967 (and improvements in the last 30yrs) | Trevisan et al. (2011) | 97/9 | 65 |
### Table 2
(Continued)

| Catalog            | Telescope                                | Resolution  | S/N  | λ Range      | Stellar Atmo | Eq. Width | CoG or SF | Solar Scale | Num. of Fe I/II lines | Stars in Hypatia |
|--------------------|-------------------------------------------|-------------|------|--------------|--------------|-----------|-----------|-------------|----------------------|-----------------|
| Tucci Maia et al. (2016) | *Magellan* Inamori Kyocera Echelle (MIKE) spectrograph (Bernstein et al. 2003) on the 6.5 m *Clay Magellan* Telescope at Las Campanas Observatory | >65000      | 400  | 3200–10000   | MARCS per (Gustafsson et al. 1975) | IRAF splot | MOOG14 per Sneden (1973) | differential analysis | 91/19                |
| Yan et al. (2016)   | FOCES echelle spectrograph on the 2.2 m telescope at Calar Alto Observatory | >40000      | >100 | 3700–9800    | MAFAGS       | spectral fitting | spectral fitting | Cu = 4.25; Fe = 7.51 | 0/8                  | 32               |
| Zenoviene et al. (2015) | Fiber-fed Echelle Spectrograph (FIES) on the Nordic Optical 2.5 m telescope | 68000       | >100 | 3680–7270    | MARCS per (Gustafsson et al. 1975) | spectral fitting (Uppsala EQWIDTH) | spectral fitting (BSYN) | differential analysis | N/A                  | 44               |
| Zhao et al. (2016)  | 1.52 m telescope at ESO using FEROS       | 48000       | 100  | 3560–9200    | MARCS per (Gustafsson et al. 1975) | ARES      | ABON2 via Spite 1967 (and improvements in the last 30yrs) | Anders & Grevesse (1989) | 97/9                  | 35               |

Note.

a Telescope/spectrograph information and the techniques for determining abundances as given by the recently added literature sources (with more than 20 stars added) into Hypatia 2.1. Please see Hinkel et al. (2014, 2016) for more details. In the header, “S/N” is the signal-to-noise reported by the literature source, “λ Range” is the wavelength coverage, “Stellar Atmo” is the stellar atmospheric model, “Eq. Width” is the package used to determine the equivalent width, “CoG or SF” designates whether the group used a curve-of-growth or spectral fitting technique (the package is specified in the former case), the “Solar Scale” is the solar normalization used by that group (differential analysis is cited where applicable), and “Num. of Fe I/II lines” lists the number of Fe I and Fe II lines.
### Table 3

Parameters in CATSUP

| Column Header | Description |
|---------------|-------------|
| HIP           | *Hipparcos* name |
| HD            | Henry-Draper catalog name |
| TYC           | TYCHO name |
| RA2000        | R.A. (epoch = 2000) |
| DE2000        | Decl. (epoch = 2000) |
| X             | geocentric x-coordinate from the Sun, in pc |
| Y             | geocentric y-coordinate from the Sun, in pc |
| Z             | geocentric z-coordinate from the Sun, in pc |
| Dist          | distance in pc (from *Gaia*) |
| Uvel          | velocity (km/s) toward Galactic anticenter (radial) |
| Vvel          | velocity (km/s) positive toward the Galactic rotation |
| Wvel          | velocity (km/s) positive toward the North Galactic Pole |
| Telf          | effective temperature of the star, in K |
| TelfSrc       | effective temperature reference source, namely PASTEL (Soubiran et al. 2016, and references therein), ExoCat (Gray et al. 2003, 2006; Valenti & Fischer 2005; Takeda et al. 2007, and V-K data, see paper) |
| logg          | surface gravity of the star |
| loggSrc       | surface gravity reference source, namely PASTEL (Soubiran et al. 2016, and references therein), ExoCat (Gray et al. 2003, 2006; Valenti & Fischer 2005; Takeda et al. 2007, and V-K data, see paper) |
| Disk          | likely origin within the disk (thin, thick, N/A) based on kinematics |
| Planet        | flag (0, 1) as to whether a planet is known to orbit the star at the time of this publication, based on the NASA Exoplanet Archive |
| Bmag          | B magnitude |
| Vmag          | V magnitude |
| BV            | B–V color |
| Single        | a true single star (=1) |
| Component     | if known to be a member of a multiple, to which component the HIP number is referring (A, B, etc.). If the HIP number includes more than one star, either a known or suspected unresolved/very faint companion, noted by a “+” symbol |
| HIP2          | if more than one star in the system has its own HIP number, the other associated HIP numbers |
| SpType        | spectral type |
| SpexSrc       | spectral type reference source, where the ADS suffix is provided in all cases. An asterisk (*) at the end of the reference indicates that the Houk spectral type was adjusted to modern MK system (using Gray et al. 2003, 2006 spectral types) following Pecaut & Mamajek (2016) |
| logRHK        | the average value of logR*/μg Ca II HK emission indices derived from literature sources |
| logRHKsources | number of sources compiled for the logR*/μg Ca II HK emission indices |
| FeH           | [Fe/H] abundance in dex |
| spFeH         | spread in [Fe/H] abundance |
| CH            | [C/H] abundance in dex |
| spCH          | spread in [C/H] abundance |
| OH            | [O/H] abundance in dex |
| spOH          | spread in [O/H] abundance |
| NaH           | [Na/H] abundance in dex |
| spNaH         | spread in [Na/H] abundance |
| MgH           | [Mg/H] abundance in dex |
| spMgH         | spread in [Mg/H] abundance |
| AlH           | [Al/H] abundance in dex |
| spAlH         | spread in [Al/H] abundance |

### Table 3 (Continued)

| Column Header | Description |
|---------------|-------------|
| SiH           | [Si/H] abundance in dex |
| spSH          | spread in [Si/H] abundance |
| CaH           | [Ca/H] abundance in dex |
| spCaH         | spread in [Ca/H] abundance |
| TiH           | [Ti/H] abundance in dex |
| spTiH         | spread in [Ti/H] abundance |
| VH            | [V/H] abundance in dex |
| spVH          | spread in [V/H] abundance |
| CrH           | [Cr/H] abundance in dex |
| spCrH         | spread in [Cr/H] abundance |
| MnH           | [Mn/H] abundance in dex |
| spMnH         | spread in [Mn/H] abundance |
| CoH           | [Co/H] abundance in dex |
| spCoH         | spread in [Co/H] abundance |
| NiH           | [Ni/H] abundance in dex |
| spNiH         | spread in [Ni/H] abundance |
| FUVmag        | FUV magnitude (AB mag) |
| FUVmagerr     | error in FUV magnitude (AB mag) |
| NUVmag        | NUV magnitude (AB mag) |
| NUVmagerr     | error in NUV magnitude (AB mag) |
| l_limit       | lower limit flag for FUV flux |
| FUVflux       | FUV flux (μJy) |
| FUVfluxerr    | error in FUV flux (μJy) |
| u_limit       | upper limit flag for NUV flux |
| NUVflux       | NUV flux (μJy) |
| NUVfluxerr    | error in NUV flux (μJy) |
| logRx         | log R*, where R* = L*/Lbol, X-ray-to-bolometric luminosity ratio or the fractional X-ray luminosity |
| logLsun       | Lbol / Lbol, bolometric luminosity in Suns** |
| iROSAT        | log 10 of X-ray flux from ROSAT (erg s⁻¹ cm⁻²) |
| lsROSAT       | log 10 of X-ray surface flux from ROSAT (erg s⁻¹ cm⁻²) |
| LROSAT        | log 10 of X-ray luminosity from ROSAT (erg s⁻¹) |
| RxROSAT       | log 10 of R*=(L*/Lbol) from ROSAT |
| fXMm          | log 10 of X-ray flux from XMM (erg s⁻¹ cm⁻²) |
| isXMm         | log 10 of X-ray flux from XMM (erg s⁻¹ cm⁻²) |
| LXXM          | log 10 of X-ray flux from XMM (erg s⁻¹ cm⁻²) |
| RxXMm         | log 10 of R*=(L*/Lbol) XMM |
| iChan         | log 10 of X-ray flux from *Chandra* (erg s⁻¹ cm⁻²) |
| isChan        | log 10 of X-ray surface flux from *Chandra* (erg s⁻¹ cm⁻²) |
| LCChan        | log 10 of X-ray luminosity from *Chandra* (erg s⁻¹) |
| RxChan        | log 10 of R*=(L*/Lbol) *Chandra* |

**Note.** "All values of 99.99 are null. **" In units of the IAU nominal solar luminosity: L_Sun = 3.828 × 10²³ W (Prša et al. 2016).

(This table is available in its entirety in machine-readable form.)

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