TWO MORE CANDIDATE AM CANUM VENATICORUM (AM CVn) BINARIES FROM THE SLOAN DIGITAL SKY SURVEY

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ABSTRACT

AM CVn systems are a select group of ultracompact binaries with the shortest orbital periods of any known binary subclass; mass transfer is likely from a low-mass (partially-)degenerate secondary onto a white dwarf primary, driven by gravitational radiation. In the past few years, the Sloan Digital Sky Survey (SDSS) has provided five new AM CVns. Here we report on two further candidates selected from more recent SDSS data. SDSS J1208+3550 is similar to the earlier SDSS discoveries, recognized as an AM CVn via its distinctive spectrum which is dominated by helium emission. From the expanded SDSS Data Release 6 (DR6) spectroscopic area, we provide an updated surface density estimate for such AM CVns of order 10^{-2} for 15 < g < 20.5. In addition, we present another new candidate AM CVn, SDSS J2047+0008, which was discovered in the course of follow-up of SDSS-II supernova candidates. It shows nova-like outbursts in multi-epoch imaging data; in contrast to the other SDSS AM CVn discoveries, its (outburst) spectrum is dominated by helium absorption lines, reminiscent of KL Dra, and 2003aw. The variability selection of SDSS J2047+0008 from the 300 deg^2 of SDSS Stripe 82 presages further AM CVn discoveries in future deep, multicolor, and time-domain surveys such as the Large Synoptic Survey Telescope (LSST). The new additions bring the total SDSS yield to seven AM CVns thus far, a substantial contribution to this rare subclass, versus the dozen previously known.

Key words: binaries: close – novae, cataclysmic variables – stars: individual (SDSS J120841.96+355025.2, SDSS J204739.40+000840.3) – white dwarfs

1. INTRODUCTION

AM Canum Venaticorum (AM CVn) systems are a select group of ultracompact binary systems, with orbital periods extending down to tens of minutes (e.g., see reviews by Warner 1995; Cropper et al. 2004; Nelemans 2005; Ramsay et al. 2007). The ultrashort orbital periods (the shortest of any known binary class) suggest that both binary components are at least partially degenerate, with a popular model invoking accretion driven by gravitational radiation from a fully- or semi-degenerate helium-rich donor (perhaps of very low mass) onto a more typical white dwarf primary. A hallmark spectroscopic characteristic of an AM CVn is a spectrum dominated by helium lines, and essentially devoid of hydrogen.

The unusual character of the prototype, AM CVn, was discovered 40 years ago (Smak 1967; Paczynski 1967), but this remarkable class has grown only slowly in membership over the intervening decades, e.g., with about a dozen members discussed in the review by Nelemans (2005). New cases of AM CVn systems are eagerly sought, as these systems may provide insights into a prior common-envelope phase, are discussed as possible SN Ia progenitors, and are plausible sources of gravitational waves (e.g., see Liebert et al. 1997; Livio & Riess 2003; Nelemans et al. 2004).

In the last few years the Sloan Digital Sky Survey (SDSS) has discovered many new cataclysmic variables (Szkody et al. 2002, 2007), and even five new AM CVn candidates. The first such SDSS AM CVn system, SDSS J1240-0159, was discovered in an early SDSS data release by Roelofs et al. (2005). In Anderson et al. (2005), hereafter Paper I, we reported the discovery of four additional AM CVn candidates (including the first eclipsing AM CVn) from the then-available SDSS spectroscopic database. All five of those earlier SDSS AM CVn candidates showed optical spectra dominated by strong helium.
emission, and this characteristic was essential in their recognition in the SDSS spectroscopic database.

In this paper, we report on another similar case, SDSS J120841.96+355025.2 (hereafter, SDSS J1208+3550), also recognized from SDSS spectra because of its strong helium emission. We also provide an updated surface density estimate for such emission-line AM CVns based on our expanded DR6 spectroscopic search area. Additionally, we report a second new AM CVn candidate, SDSS J204739.40+000840.3 (hereafter, SDSS J2047+0008), that was discovered via time-domain imaging data as part of the SDSS-II supernova survey (Frieman et al. 2007). As initially announced in a telegram by Prieto et al. (2006), SDSS J2047+0008 shows novae-like outbursts in multi-epoch SDSS imaging. Moreover, the optical spectrum of SDSS J2047+0008 at outburst shows helium absorption lines, in contrast to the spectra of the other SDSS discoveries, and more similar to some other well-known AM CVn systems such as KL Dra and 2003aw (Jha et al. 1998; Filippenko & Chornock 2003). Including the two additions discussed herein, the total SDSS yield thus far is seven new AM CVn candidates, a substantial contribution to expanding the membership of this rare subclass, compared to the approximately dozen cases known prior to SDSS.

2. SDSS J120841.96+355025.2, AND A SEARCH OF SDSS DR6 FOR SIMILAR AM CVn CANDIDATES

The SDSS is a multi-institutional and international project creating an optical digital imaging and spectroscopic data bank of a region approaching $10^4\,\text{deg}^2$ of sky, primarily centered on the north Galactic polar cap. Imaging and spectroscopic data are obtained by a special purpose 2.5 m telescope, at Apache Point Observatory, New Mexico, equipped with a large-format mosaic camera that can image $\sim 10^2\,\text{deg}^2$ per night in five filters ($u, g, r, i, z$), along with a multifiber spectrograph that obtains 640 spectra within a 7 deg$^2$ field. The imaging database is used to select objects for the SDSS spectroscopic survey, which includes $(\lambda/\Delta\lambda \sim 1800)$ spectrophotometry covering 3800–9200 Å for 10$^6$ galaxies, 10$^5$ quasars, and 10$^8$ stars. Technical details on SDSS hardware, software, and astrometric, photometric, and spectral data may be found in a variety of papers, e.g., Fukugita et al. (1996), Gunn et al. (1998), Lupton et al. (1999), York et al. (2000), Hogg et al. (2001), Stoughton et al. (2002), Smith et al. (2002), Pier et al. (2003), Ivezić et al. (2004), and Gunn et al. (2006). A description of the most recent SDSS Public data release (Data Release 6; hereafter, DR6) is given by Adelman-McCarthy et al. (2008).

As discussed in Paper I, the SDSS collaboration includes a “Serendipity Working Group” which is engaged in selection and examination of a large number of atypical SDSS spectra; such spectroscopic selection and visual examinations have led to the initial discovery of the bulk of the previous SDSS AM CVns. Their distinctive spectra, similar to cataclysmic variables but with helium rather than hydrogen emission lines, drew our special attention to these cases.

Similarly, SDSS J1208+3550, the first new AM CVn candidate discussed in this paper, was initially found as a serendipitous discovery during a search of the DR5 SDSS spectroscopic database for DQ white dwarfs (Halford et al. 2005). The discovery spectrum of SDSS J1208+3550 is displayed in Figure 1, and strongly resembles the previous SDSS AM CVn finds, with prominent broad emission at He i 3888, 4026, 4471, 4921, 5015, 5875, 6678, 7065, and 7281 Å; for example, the equivalent width and full width at half maximum of He i 5875 Å, respectively, 28 Å and 1600 km s$^{-1}$. There is also weaker He II λ4686 emission. Though the signal to noise is modest, the Figure 1 spectrum again suggests multi-peaked helium emission, presumably from an accretion disk. As with most previous SDSS AM CVn discoveries, SDSS J1208+3550 was targeted for a spectrum because of its unusually blue color in SDSS imaging data, having been selected by several independent (but overlapping) target selection methods including “hot-standard star,” “quasar,” “serendipity,” and “white-dwarf” algorithms. Basic astrometric and photometric data from SDSS are provided in Table 1, though, of course, AM CVns may be variable, and so the tabulated SDSS J1208+3550 magnitudes are only indicative of its character at the epoch of the SDSS observations.

Because visual and other serendipitous searches of spectra, such as those which initially revealed SDSS J1208+3550, could be biased and incomplete, we have also algorithmically sifted through the SDSS DR6 spectroscopic database for any further new SDSS AM CVn candidates showing strong helium emission. This algorithmic search is directly analogous to that discussed in detail in Paper I (which was based largely on the smaller DR4 spectroscopic area). In the current paper, this algorithmic search was applied to DR6 plates encompassing more than 7000 deg$^2$ and a million spectra.

In particular, we queried the DR6 spectroscopic database to return a list of objects with spectra for which the SDSS pipeline data reduction algorithms (Stoughton et al. 2002) found any emission line with equivalent width $\geq$ 3 Å, with wavelength centered within 20 Å windows around either He II λ4686 or He I λ5875. These are typically the highest equivalent-width lines among the Paper I AM CVn candidates (initially found in the visual search of earlier SDSS spectroscopic plates). The choice of minimum equivalent width in this algorithmic search, of course, limits such discoveries to AM CVns with helium.

\footnote{This object was subsequently independently recovered by others both inside and evidently outside the SDSS collaboration; for example, there is a point labeled “J1208” in Figures 2 and 4 of Roelofs et al. (2007).}
The AM CVn systems occupy a relatively sparse and distinct portion of SDSS. SDSS DB white dwarfs from Harris et al. (2003) are also plotted (open circles).

For additional comparison, the colors of ten AM CVns (solid, black triangles) with reliable photometry, which fall within the SDSS DR6 imaging area. For additional comparison, the colors of AM CVn candidates that might have slipped through the pipeline algorithmic emission-line search. Among these candidates are ten whose magnitudes lie in the range $13 < g < 20.5$; this is an approximate range in which SDSS provides high quality imaging photometry and spectroscopy. We construct a three-dimensional (hereafter, 3D) box in $u - g$, $g - r$, and $r - i$ multicolor space that encompasses those ten AM CVns; we enlarge the boundaries of this box a little in each dimension, as shown in Figure 2, to encompass not just the SDSS colors of these ten AM CVns, but their colors plus 3σ color errors as well.

(In constructing this box, we do not consider three additional AM CVns in the SDSS area that were either too bright or too faint for reliable photometry. Nor do we consider the $i - z$ color distribution of the AM CVns, as the $z$-band photometric errors are large for most of these blue AM CVns imaged in SDSS.)

We then visually examined the 8300 objects with spectra in SDSS DR6, whose colors in SDSS imaging fall within this 3D multicolor box. This additional perusal of SDSS DR6 color-selected spectra again recovered all five previously published SDSS AM CVns, but revealed no additional strong emission-line AM CVn candidates aside from SDSS J1208+3550. Thus, SDSS J1208+3550 (originally from DR5) is the solitary new emission-line candidate AM CVn discussed herein.

Following our initial 2005 discovery of SDSS J1208+3550, in 2006-2007 we then obtained follow-up exploratory optical lightcurve and X-ray flux observations of this new AM CVn system. We used the SPlcam CCD imager with an SDSS $g$-band filter on the ARC 3.5 m to obtain optical lightcurve information from brief time-series sequences (spanning about 1–2 h each) on four distinct nights: 2006 February 1, 2006 March 3, 2006 April 1, and 2007 January 12 (all UT). Several of these nights were not photometric, but differential photometry was obtained relative to (the same) three brighter comparison stars in each image. The time resolution between individual exposures was in the range 1.4–2.4 min for all nights. Unfortunately, these data reveal no convincing periodic optical modulation for periods in the range of about 4–40 min, and with an amplitude limit of a few hundredths of a magnitude. Longer-timespan observations would be especially useful to obtain similar sensitivity to photometric modulations at (plausibly) longer orbital periods.

We also obtained a ∼3000 s X-ray exposure of SDSS J1208+3550 from the Chandra X-ray Observatory on 2007 March 23 (UT). These data were collected in VFAINT mode allowing us to utilize the full 5 × 5 pixel event island and thus reduce ACIS particle background. We reprocessed the level 1 events file in order to leverage this additional information and thereby filter for hot pixels, cosmic rays, background events, bad grades, and good time intervals. SDSS J1208+3550 is strongly detected in our Chandra data, with 45 counts in a medium energy (0.5–4.5 keV) X-ray band; background contributions are evaluated with a monenergetic (0.5 keV) exposure map. For an assumed blackbody X-ray spectrum with $kT = 0.7$ keV, e.g. similar to that inferred for ES Cet (Strohmayer 2004), these Chandra medium band data imply an unabsorbed 0.2–10 keV flux of about $10^{-10}$ erg cm$^{-2}$ s$^{-1}$. This measured X-ray flux for SDSS J1208+3550 is reassuringly similar (within about a factor of 2) to what we predicted based on the typical X-ray to optical flux ratios of other AM CVns.

### Table 1

| R.A., Decl. name | $u$ | $g$ | $r$ | $i$ | $z$ | Epoch |
|-----------------|-----|-----|-----|-----|-----|-------|
| J120841.96+35502.5 | 18.80 | 18.79 | 18.94 | 19.09 | 19.17 | 2004 Apr 16 (UT) |
| J204739.40+000840.3 | 17.43 | 17.45 | 17.76 | 18.02 | 18.27 | 2006 Oct 12 (UT) |

Figure 2. SDSS color–color diagrams highlighting AM CVn systems. The small black points show the colors of random stellar objects having reliable photometry, derived from 100 deg$^{-2}$ of the SDSS. Overplotted are the SDSS colors of ten AM CVns (solid, black triangles) with reliable photometry, which fall within the SDSS DR6 imaging area. For additional comparison, the colors of SDSS DB white dwarfs from Harris et al. (2003) are also plotted (open circles). The AM CVn systems occupy a relatively sparse and distinct portion of SDSS multicolor space, as depicted by the dotted boxes.
3. SDSS J204739.40+000840.3,
A TIME-DOMAIN-SELECTED AM CVn CANDIDATE

Since the completion of Paper I, an entirely new opportunity for AM CVn searches has emerged from SDSS, and here we also report a new AM CVn, SDSS J2047+0008, discovered in that very different manner. SDSS J2047+0008 (originally known internally as ”candidate 15204”) was instead discovered in the course of the SDSS-II supernova search (Frieman et al. 2007), which surveys the 300 deg^2 SDSS “Stripe 82” region via multi-epoch imaging. Basic data on SDSS J2047+0008 are displayed in Table 1, which reflect the object’s state (in outburst) on UT 2006 October 12 (MJD 54020.125); its color on this epoch also falls nicely within the 3D multicolor box found for other AM CVns shown in Figure 2.

This new object is markedly variable. As may be discerned from the Figure 3 long-term lightcurve, SDSS J2047+0008 has been imaged with SDSS-I and SDSS-II Stripe 82 observations at 60 epochs over an eight-year timespan (Ivezić et al. 2007; Holtzman et al. 2008), but was unnoticed until its outburst in the fall of 2006, when caught as part of the SDSS-II supernova discovery program. The large amplitude variations strongly suggests nova-like outbursts in this system.

The SDSS-II lightcurve of SDSS J2047+0008 shown in Figure 4 has been expanded to highlight the fall 2006 discovery and outburst observations. SDSS J2047+0008 (not too surprisingly) appears to have a stronger ultraviolet excess in its brighter state. A potentially interesting aspect of the lightcurve is that this object may show some cycling between high and intermediate states while fading; such behavior, for example, has been reported for the (outbursting) AM CVn system V803 Cen (Patterson et al. 2000; Kato et al. 2004).

Prompted by its dramatic variability in SDSS-II imaging, an optical spectrum of SDSS J2047+0008 was taken on UT 2006 October 19 (MJD 54027) with the MDM 2.4 m Hiltnier telescope (plus OSU Boller and Chivens Spectrograph), and is shown in Figure 5. There is clearly a blue continuum with shallow helium absorption lines of He i 3820, 3867, 3927, 4009, 4026, 4144, 4388, 4471, 4921, and perhaps 5875 Å. This spectrum is unlike traditional novae, but similar to the other objects such as KL Dra (also known as 1998di; Jha et al. 1998) and 2003aw (Filippenko & Chornock 2003), which were also noticed as hydrogen deficient novae, and subsequently classified as likely AM CVns.

The absorption-line spectral character of this new variability-selected AM CVn system, SDSS J2047+0008, is in strong contrast to the other SDSS discovered AM CVns, which were all recognized in the SDSS database by virtue of their helium-dominated emission line spectra. The SDSS databases (including the SDSS-II Stripe 82 data) may include interesting additional AM CVns similar to SDSS J2047+0008, still awaiting recognition.

A follow-up lightcurve of SDSS J2047+0008 in outburst, and with time resolution potentially sensitive to a strong
orbital modulation, was obtained with the WIYN telescope and MiniMosaic CCD array on 2006 November 1 (UT). Exposures were 300 s long through a Harris R-band filter, and each exposure had a 2 min readout time, yielding 19 images over a 2.5 h timespan. Differential photometry was performed by comparison to nearby stars with known SDSS calibrations. A star 15° to the southeast of SDSS J2047+0008 is estimated to have a R-band magnitude of 16.46 ± 0.02 mag by converting from SDSS magnitudes. From this approximate calibration, the average magnitude of SDSS J2047+0008 over the WIYN observing run was found to be $R = 20.58$, but with significant variations of 0.2 mag over the 2.5 h span. Additional lightcurve data taken at good time-resolution may be useful in determining an orbital period; however, a quality lightcurve outside of outburst may prove difficult, given the faintness of the object in quiescence (Figure 3).

4. DISCUSSION

Our spectroscopic search for emission-line AM CVn candidates from SDSS now includes spectroscopic plates extending through DR6, and provides some updated, though approximate, constraints on the surface density of AM CVns. These constraints remain uncertain as SDSS spectroscopy (purposefully emphasizing the main galaxy and quasar surveys) is highly incomplete and non-uniform across the sky even for emission-line AM CVn candidates (see details in Paper I).

The main SDSS spectroscopic survey, along with the SDSS-II SEGUE survey, include spectroscopic plates which encompass 7400 deg$^2$ of sky and 1.3 million spectra. SDSS has discovered six emission-line AM CVn candidates in this region, including SDSS J1208+3550 presented herein; all six were initially selected as interesting for spectroscopic follow-up based on their blue colors in SDSS imaging, with subsequent recognition as AM CVns in the SDSS spectroscopic database because of their helium-dominated emission line spectra (Roelofs et al. 2005; Paper I, this paper). All six of these had $15 < g < 20.5$ at the epochs of both SDSS imaging and SDSS spectrophotometry, and this is also a plausible range for both high-quality SDSS imaging and spectra. (For example, SDSS spectroscopy is restricted to $m > 15$ to avoid fiber cross-talk; and for blue stellar objects, $m < 20.5$ is the typical faintest limit for routine spectroscopic target selection.) Thus, an approximate, conservative lower limit on the surface density of AM CVns is $>1/1000$ deg$^{-2}$ for $15 < g < 20.5$.

To proceed further, albeit less securely, requires an estimate of the incompleteness of SDSS spectroscopy for similar emission-line AM CVn candidates. The incompleteness even for very similar AM CVn candidates arises from several complicating factors, including: the emission-line AM CVn candidates found in SDSS were selected for spectroscopy by several distinct target selection algorithms, each differing in their specific color-selection criteria and limiting magnitudes; and some of these target selection algorithms actually receive spare spectroscopic fibers only rarely and non-uniformly over the sky, when the main galaxy and quasar surveys do not consume all available fibers for a given spectroscopic plate.

But, as a rough estimate of such spectroscopic incompleteness for similar AM CVn candidates, we consider again the same 3D box in $u - g, g - r, r - i$ multi-color imaging space described in Section 2 (also see Figure 2). In the DR6 imaging area there are about 2.97 deg$^{-2}$ stellar objects with such colors and $15 < g < 20.5$; in the DR6 spectroscopy area, the surface density of such objects actually having SDSS spectra taken is about 1.14 deg$^{-2}$. Thus, SDSS spectroscopy would be of order 38% complete for such objects, naively assuming uniform spectral coverage throughout the 3D box.

Alternatively, one might consider a somewhat smaller box in multicolor space that extends only to objects as red as about $u - g < 0.11$; as may be discerned from Figure 2, this smaller 3D box excludes only one of the (ten) known AM CVns with reliable photometry in DR6. In the DR6 imaging area, such a smaller 3D multicolor box includes a typical surface density of about 1.04 deg$^{-2}$ of such objects. The surface density of such SDSS objects also having spectroscopy is about 0.40 deg$^{-2}$, suggesting (naively) a similar SDSS spectroscopic overall completeness of order 39%. In fact, the situation is more complicated, as such spectroscopic completeness depends on various magnitude limits and may vary across even this smaller multicolor box, due to the differing target selection algorithms used. More elegant estimates may be tied to AM CVn binary period and temperature/color relations; see Roelofs et al. (2007) for an excellent example of this approach.

As an intermediate improvement on our simple estimate above, we have considered the SDSS spectroscopic completeness (accounting for differences in DR6 imaging and spectroscopic survey areas) in these same 3D multicolor boxes for each 0.5 magnitude bin in the range 15.0 $< g < 20.5$. Our spectroscopic completeness estimates are very similar when considering either the larger or smaller 3D multicolor boxes, so the precise box color boundaries may not be critical; completeness (for morphologically stellar objects) ranges from a low of 10–20% at the very brightest and faintest ends, maximizing at just under 70% spectral completeness at $g = 18 - 19$. Within the faintest four bins spanning $g = 18.5 - 20.5$, where the great bulk of SDSS 3D color-selected candidates would in any case fall, and which also encompasses all the emission-line selected AM CVns from SDSS, the lowest completeness estimate is 24%. We thus adopt the latter value as a representative lower limit to the SDSS spectroscopic completeness within the 3D boxes shown in Figure 2. This updated completeness estimate is also quite similar to the $\sim$20% we suggested in Paper I, and even to the more sophisticated completeness estimates of Roelofs et al. (2007) in a similar magnitude regime (and for a wide range in AM CVn binary periods in their model).

Broadly then, the surface density of AM CVns with $15 < g < 20.5$, similar to those with strong helium emission as found in the SDSS spectroscopic database, might be expected to be approximately in the range from $10^{-3.1}$ deg$^{-2}$ (with no spectroscopic completeness correction) to about $10^{-2.5}$ deg$^{-2}$ (adopting representative spectroscopic completeness of $\sim$24%). Of course, there are additional AM CVns aside from those typically showing strong emission lines; indeed, SDSS J2047+0008 discussed in Section 3 is the most recent example.

In one commonly discussed scenario (e.g., Nelemans 2005), the youngest members of the AM CVn class are thought to be those with the highest mass-transfer rates and shortest periods (<20 min), and these “high-state” systems show predominantly helium in absorption in their optical spectra. In that scenario, they then evolve into somewhat longer periods as the binary widens and the mass transfer rate continues to decrease; in this intermediate stage, perhaps with 20–40 min periods typical, the objects may show nova-like outbursts, and display both high-state (absorption) and low-state (emission) spectra. Then finally there is a late stage (perhaps with typical 40–60 min binary
periods) in which AM CVns are primarily low-state sys-
tems with predominantly emission-line spectra. Other scenarios
similarly place an approximate dividing line between mainly
emission-line and mainly absorption-line systems at binary pe-
riods of about 30 min (Roelofs et al. 2007). The relative pop-
ulations in these various stages are not yet well constrained
empirically, but at least some models (Roelofs et al. 2007) pre-
dict significantly fewer of the shorter-period systems, and so
the surface density of all AM CVns might be comparable to the
estimate above based on emission-line AM CVns only.

At first glance these fiducial surface density limits are also
compatible with our discovery of the one variability-selected
case, SDSS J2047+0008, from the SDSS Stripe 82 survey
region, given: (i) the uncertainty in the above surface density
estimates; (ii) the 300 deg² areal coverage of time-domain
imaging of the Stripe 82 supernova survey region; (iii) the
faintness in quiescence (often g > 22) of SDSS J2047+0008,
a regime for which presumably the surface densities are even
higher; and (iv) the large uncertainty in the relative populations
among high, intermediate, and low-state AM CVns.

Despite recent down-sizing in population model estimates
for AM CVns based on essentially this same set of SDSS
objects (Roelofs et al. 2007), our current surface density
estimates suggest that upcoming large-area multicolor plus
time-domain surveys such as the Large Synoptic Survey
Telescope (LSST)—with their excellent time-sampling and color
range, and extending to fainter magnitudes than the SDSS—may
still provide an excellent opportunity to discover dozens or
even hundreds of additional AM CVns. Such a large area,
multicolor plus time-domain sample might especially extend
uniform surveys to the intermediate- and high-state AM CVn
populations that (often) lack emission lines, and which may be
much more difficult to efficiently identify in multicolor-only
surveys.

In any case, along with SDSS J1208+3550 and J2047+0008
presented herein, SDSS-I and SDSS-II have thus far yielded a
total of seven new AM CVn candidates (Roelofs et al. 2005;
Anderson et al. 2005; this paper). The SDSS is thus providing a
substantial expansion to this rare object class, compared to the
approximately dozen AM CVns previously known.

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