Statistical ages and the cooling rate of X-ray dim isolated neutron stars

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ABSTRACT
The cooling theory of neutron stars is corroborated by its comparison with observations of thermally emitting isolated neutron stars. An important ingredient for such an analysis is the age of the object, which, typically, is obtained from the spin-down history. This age is highly uncertain if the object’s magnetic field varies appreciably over time. Other age estimators, such as supernova remnant ages and kinematic ages, only apply to few handful of neutron stars. We conduct a population synthesis study of the nearby isolated thermal emitters and obtain their ages statistically from the observed luminosity function of these objects. We argue that a more sensitive blind scan of the galactic disk with the upcoming space telescopes can help to constrain the ages to higher accuracy.

Key words: stars: magnetic fields - stars: neutron - magnetars

1 INTRODUCTION
The observed thermal states of isolated neutron stars have become the primary source to glean useful and interesting information about the internal structure of neutron stars (NSs). Reconciliation of theoretical cooling curves with observations of nearby isolated cooling NSs is a challenging task (see for e.g. Yakovlev & Pethick (2004); Page et al. (2006) for a comprehensive review). On the theoretical front, the problem arises from incomplete knowledge of the composition and equation of state (EOS) of matter in the NS core at supernuclear densities ($\rho > 10^{14} \text{gcm}^{-3}$). Many possibilities can be realized: Depending on the composition the EOS can be either soft or stiff, where the stiffness characterizes the compressibility of matter, and strongly depends on the internal degrees of freedom of the system (e.g. Schaab et al. (1996)). For example, for a polytropic EOS, $P = K \rho^\Gamma$, a larger adiabatic index $\Gamma$ yields stiffer EOS. Such an EOS generally produces larger maximum masses and radii of NSs than its softer counterpart. Softer EOSs can be obtained by the introduction of phase transitions in the theory where the core of the NS may be composed of boson condensates, quark or hyperonic matter. However, the presence of these at nuclear densities has been ruled out from the observation of the inner core, such that it affects the choice of the neutrino cooling process that is dominant in the first $10^4 - 10^5$ yrs of its evolution (see for e.g. Yakovlev et al. (2001) for a detailed description of all the neutrino emission processes in NSs).

Observations of isolated cooling NSs present its own set of challenges in determining their cooling rate. Here, one is interested in detecting radiation emanating from the surface of the NS which is complicated by the non-thermal emission from the magnetosphere. Also, the non-uniform heating of the crust due to energetic particles accelerated in the magnetosphere render accurate determination of effective temperatures hard (see for e.g. the review by Ozel (2013) on surface emission from NSs). Also, the unknown composition of NS atmospheres leads to the overestimation of their temperatures when fitting their spectra with a blackbody (e.g. Lloyd et al. (2003)). Apart from the uncertainties involved in the spectral modelling of NS surface emission, uncertainties in their distances can also contribute to poor effective temperature and luminosity estimates. Furthermore, to place observed isolated sources on cooling curves, accurate ages are needed that may be hard to obtain as we discuss below.

In this study, we show that, for a large sample, ages of isolated thermal emitters can be derived from statistical arguments. As the sample size grows, the statistical error diminishes. We look at a small group of thermally emitting NSs discovered in the ROSAT all-sky survey in Sec. 2 and derive their ages statistically in Sec. 3. Lastly, we discuss

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the possibility of improving the meager sample of isolated thermal emitters by detecting more such objects in the upcoming eROSITA all-sky survey.

2 THE MAGNIFICENT SEVEN

Nearby isolated cooling neutron stars are particularly important for confronting cooling models with observations. They were discovered by Einstein, ROSAT, and ASCA space telescopes (Becker & Pavlov 2002), and were further observed with the extremely sensitive and high resolution high-energy space telescopes Chandra and XMM-Newton. Among all the discovered objects, the most interesting are the seven radio-quiet thermally emitting isolated NSs (a.k.a. the magnificent seven, M7) discovered in the ROSAT all-sky survey (RASS) (see for e.g. Haberl 2007, for a review). These radio-quiet objects radiate predominantly in X-rays with high X-ray to optical flux ratios, $f_X/f_{opt} > 10^4$. Their soft X-ray spectra are reasonably well fit by an absorbed blackbody-like spectrum with $kT \lesssim 100$ eV and a hydrogen column density $n_H \sim 10^{20}$ cm$^{-2}$, indicating small distances $d \sim$ few $\times$ 100 pc. That the thermal emission is coming from majority of the stellar surface is confirmed by the small pulse fractions $\lesssim 20\%$ of the X-ray light curves. Spin periods ranging from 3 - 12 s have been measured for all but one (RX J185635-3754) of the M7 objects (see for e.g. Mereghetti 2011, Table 1). This in conjunction with the measured spin-down rates, $P \sim 10^{-14} - 10^{-13}$ s$^{-1}$, yields an estimate of the polar magnetic field strengths $B_0 \sim 10^{13}$ G and the characteristic spin-down ages $\tau_c \sim 10^6$ years. Measurements of the high proper motions of three of the M7 objects and their association thus established to the Sco OB2 complex comprising the Gould Belt yield slightly smaller kinematic ages. This discrepancy strongly suggests that the spin-down ages are overestimates and the M7 objects in reality are much younger.

2.1 Spin-Down Ages: Poor Age Estimators

According to the standard magnetic dipole model of pulsars (Shapiro & Teukolsky 1983), a rotating NS with a polar magnetic field spins down over time by emitting magnetic dipole radiation. From the rate of change of the angular frequency $\dot{\Omega}$, the spin-down age of the NS can be readily determined

$$\tau = \frac{\Omega}{2|\dot{\Omega}|}.$$  

The spin-down law implicitly assumes that none of the other physical characteristics of the pulsar vary over time. This may not be the case and, in general, the spin-down law (Lyne & Graham-Smith 2006) written as the following can be allowed to include variation of $B_0$, the moment of inertia $I$, and the angle between the rotation axis and the magnetic dipole axis $\alpha$, so that

$$\frac{d\Omega}{dt} = -\kappa(t)\Omega(t)^n,$$  

where $\kappa(t)$ is usually assumed to be a constant and $n = 3$ is the braking index for magnetic dipole braking. Any change in $\kappa$ with time naturally yields ages of pulsars that are in conflict with their spin-down ages; Generally, the spin-down age should only be taken as a rough estimate to aid in calculations.

An independent age estimate is provided by the age of the associated supernova remnant (SNR) or massive star cluster for younger objects. Establishing such an association for older NSs may prove to be difficult since SNRs fade away in ~ 60 kyr, and in the same time, due to natal kicks (~ 500 km s$^{-1}$), NSs may move significantly far away from their birth sites (Frail et al. 1994). We plot the spin-down and the estimated SNR ages for young pulsars ($\tau < 10^5$ yrs), central compact objects (CCOs), and magnetars (SGRs and AXPs) along with their timing properties (see for e.g. Becker 2009, for a review) in Fig. 1 and it is clear that for most NSs the spin-down age is a poor age estimator. The objects that have SNR ages smaller than their spin-down ages can be explained by having a braking index less than the canonical value, $n < 3$. An excellent example supporting this notion is the Vela pulsar which has a very small breaking index $n = 1.4 \pm 0.2$ estimated from an impressive 25-year long observation (Lyne et al. 1990), albeit under the assumption that $\kappa$ is still a constant. This yields a spin-down age of 25.6 kyr, making it appear more than twice as old as its age inferred from the standard magnetic braking scenario. This result is well supported by the estimated age of the Vela SNR ($t_{SNR} \sim 18 - 31$ kyr) (Aschenbach et al. 1997).

On the other hand, for objects that have spin-down ages larger than that of their true ages, that may be inferred from their associated SNR ages, it has been argued that the magnetic moments decrease in strength over time. There are three main mechanisms by which magnetic fields can decay in isolated NS, namely Ohmic dissipation, ambipolar diffusion, and Hall drift (Goldreich & Reisenegger 1992). The timescale over which the field decays substantially due to these processes (see for e.g. Heil & Kulkarni 1998) determines the dominating process at different stages in the evolution of an isolated NS.

An important consequence of field decay is that it leads to an overestimation of the real age of the NS. Following the
3 TRUE AGE ESTIMATES OF ISOLATED NEUTRON STARS

The M7 objects don’t have any SNR or massive star cluster associations. Therefore, ages for these objects have been derived from their $P$ and $\dot{P}$ measurements. In addition, since they are nearby objects ($d \lesssim 500$ pc), and due to their large proper motions, kinematic ages became a possibility and have been estimated for only three of the group members (see Table 1). In this case, one finds that the spin-down ages are larger by a factor of 3–10 than the kinematic ages. Accurate age estimates are extremely important in determining the cooling behavior of isolated NSs. Overestimated ages used to fit model cooling curves can obscure the determination of the true thermal state of these objects.

3.1 Age Estimates from Population Synthesis

In the following, we estimate the true ages of the M7 members by a method that is motivated by another method devised by Schmidt (1968) and then applied by Huchra & Sargent (1973) to calculate the luminosity function of field galaxies. The original idea is implemented as follows. An apparent magnitude limited sample is first obtained and it exactly reproduces the true luminosity function within statistical errors. In the past few million years, and furthermore, the neutron stars progress from bright to faint luminosities as the age in the same (albeit unknown) way. Under these assumptions we can deduce the age of a neutron star of a given

$$t(M) = \frac{1}{\beta} \int_{-\infty}^{M} \Phi(M')dM'dV$$

where $\beta$ is the neutron-star birthrate per unit volume.

3.2 RASS and Population Synthesis

In the following, we develop a slight variant of the Schmidt (1968) estimator to calculate the true ages of the members of the M7 family. The method we develop cannot be model independent as the distribution of NSs, unlike that of galaxies over large scales, is not uniform. Since the progenitors of NSs mainly reside in the arms of a spiral galaxy, and for a natal kick velocity of, say $\sim 500$ km s$^{-1}$, the NSs only travel a distance of $\sim 50$ pc from their birth sites within $\sim 10^5$ years. This is small compared to the scale height of the thin disk $\sim 300$ pc (Binney & Merrifield 1998). As a result, the Schmidt (1968) estimator cannot be used here. Instead, we look at the NS progenitor population and calculate the normalization for each M7 member by counting the number of massive OB stars that are found in the accessible volume $V_{\text{max}}$ for that object. The population synthesis method is given in our earlier study (Gill & Hély 2005), and essentially requires the assumption of the luminosity function and spatial distribution of massive OB stars in the galaxy (Bahcall & Soneira 1980), and the distribution of HI, which we model as a smooth exponential disk both radially and vertically (Foster & Routledge 2003).

All M7 objects were discovered by ROSAT which scanned the whole sky with a limiting count rate of $0.015$ cts s$^{-1}$ in the energy range $\sim 0.12 - 2.4$ keV (see Hünsch et al. 1999 for more details). The complete survey covers 92% of the sky for a count rate of 0.1 cts s$^{-1}$ (Voges et al. 1999), and has yielded the most complete and sensitive survey of the X-ray sky. Therefore, it provides a perfect flux-limited sample for our study. Next, we calculate the weights for each object in the sample by simulating the RASS and finding the total number of massive OB stars in the volume $V_{\text{max}}$, such that the estimated age is given in terms of the typical age of their progenitors $t_{\text{OB}}$.

$$t_i \sim t_{\text{OB}} \sum_{j=1}^{N_j} \frac{N_j}{N_{j,\text{OB}}}$$

where $N_j$ is the number of NSs in a small absolute magnitude bin of size $dM$ centered at $M_j$. Since the sample is of marginal size, $N_j = 1$ in this case. Then, $1/N_{j,\text{OB}}$ gives the number of massive OB stars per $j$th object in the sample. The ages of NS progenitors are highly uncertain and are usually obtained by estimating the main sequence turn-off ages of the massive star cluster to which the NS may be associated (see e.g. Smartt 2004 for a review). Typical ages of $\sim 3 - 15$ Myr have been estimated for the progenitors of NSs and magnetars. Figer et al. (2005) report the age of the cluster of massive stars, containing three Wolf-Rayet stars and a post main-sequence OB supergiant, associated to the magnetar SGR 1806–20 to be roughly 3.0–4.5 Myr. Also, Muno et al. (2006) report an age of 4 ± 1 Myr for the...
cluster Westerlund 1 which seems to be the birth site of another magnetar CXOU J164710.2 − 455216. In yet another study, Davies et al. (2009) find the age of the cluster associated to the magnetar SGR 1900 + 14 to be 14 ± 1 Myr. Since the spin-down ages of magnetars are much smaller (≈ 10^{10} yr) than that of the clusters, the notion that the cluster age reflects the age of the progenitor, under the assumption of coevality of its members, is a valid one. In the case of SGR 1806 − 20 and CXOU J164710.2 − 455216, both groups find that the progenitor must be a massive star with \( M > 40 M_\odot \), except in the last study where the progenitor of SGR 1900+14 is claimed to be a lower mass star with initial MS mass of 17 ± 2 M_\odot. Notwithstanding this last result, it has been claimed that magnetars may be the progeny of only sufficiently massive stars (\( M \gtrsim 25 M_\odot \)) (Gaensler et al. 2005) that would, otherwise, have resulted in the formation of a black hole. Although the members of the M7 family are endowed with fields an order of magnitude higher than the normal radio PSRs, they are not magnetars and can be argued to be the descendants of progenitors not much more massive than that of the normal radio PSRs. In that case, it is expected that the progenitor age \( t_{\text{OBS}} \) will be considerably longer in comparison to that of magnetar progenitors. An upper limit on the ages of M7 progenitors can be placed from the age of the Gould Belt, \( t_{\text{OBS}} \lesssim t_{\text{GB}} \sim 30 − 60 \) Myr (Torra et al. 2000).

From Eq. [1] the ages of the sample objects are proportional to \( t_{\text{OBS}} \), thus significant uncertainty in the progenitor age will yield erroneous ages. To circumvent this problem, we normalize \( t_{\text{OBS}} \) such that the estimated age of RX J1856.5 − 3754 matches its kinematic age \( t_{\text{kin}} = 0.46 ± 0.05 \text{ Myr} \), which has been measured using its high proper motion (Tetzlaff et al. 2011). This yields a slightly larger age for the progenitor \( t_{\text{OBS}} \sim 55 \) Myr. The corresponding SN rate in the Galaxy is \( \sim 1 \) per century, in good accord with published estimates, for example \( 1.9 ± 1.1 \) reported by Diehl et al. (2006).

Over the last few years, two new candidates have been added to the M7 group. The first object, IRXS J141256.0 + 792204 dubbed Calvera (Rutledge et al. 2008), was actually cataloged in the RASS Bright Source Catalog (Voges et al. 1999) for having a high X-ray to optical flux ratio \( F_X/F_\odot > 8700 \). However, its large height above the Galactic plane (\( z \approx 5.1 \text{ kpc} \), requires a space velocity \( v_z \geq 5100 \text{ km s}^{-1} \), presents a challenge for its interpretation as an isolated cooling NS like the M7 members (see Rutledge et al. 2008 for a detailed discussion). Also, recent X-ray observations of Calvera done with the XMM-Newton space telescope found unambiguous evidence for pulsations with period \( P = 59.2 \) ms (Zane et al. 2011). The authors of this study argued that Calvera is most probably a CCO or a slightly recycled pulsar. The uncertainty in its nature (see Halpern (2011)) doesn’t warrant inclusion into our sample of radio-quiet isolated NSs. The second object 2XMM J104608.7 − 594306 (Pires et al. 2009), discovered serendipitously in an XMM-Newton pointed observation of the Carina Nebula hosting the binary system Eta Carinae, appears to be a promising candidate (see Table I for properties). This object was not detected in the RASS due to its larger distance (\( z \approx 2.3 \text{ kpc} \), based on its association to the Carina nebula) and higher neutral hydrogen absorption column density (\( N_H = 3.5 ± 1.1 \times 10^{21} \text{ cm}^{-2} \)). Therefore, the accessible volume \( V_{\text{max}} \) is the ROSAT surveyed volume plus the additional volume probed by the XMM-Newton’s pointed observation.

In Table II we provide all the relevant data on the sample objects including the spectral fit parameters that were used to simulate the RASS to obtain \( V_{\text{max}} \). We take the calculated ages and plot them against the effective temperatures observed at infinity in Fig. 2. The errorbars on the ages correspond to the maximum of the difference in ages obtained due to uncertainties in \( T_{\text{obs}} \), \( N_H \) (these two parameters are covariant), and the distance. The blackbody temperature \( T_{\text{bb}} \) is obtained by fitting a blackbody spectrum to that observed from the source. The temperature, thus, corresponds to the color temperature of the object and is an over-estimation of the effective temperature \( T_{\text{eff}} \) due to strong energy dependence of the free-free and bound-free opacities of the photosphere (see for e.g. Lloyd et al. (2003)). The effective temperature is obtained from \( T_{\text{bb}} \) using a color correction factor \( f_c = T_{\text{bb}}/T_{\text{eff}} \) where 1 \( \lesssim f_c \lesssim 1.8 \) (e.g. Özel (2013)). For comparison, we also plot some cooling curves from Yakovlev & Pethick (2004), where the non-superfluid (No SF) model for a 1.3 M_\odot cannot explain the data. Other model curves show NS cooling behavior if proton superfluidity in the core is taken into account (see Yakovlev & Pethick (2004) for more details on the 1P and 2P models).

### 3.3 Statistical Ages Vs The True Ages

The ages of isolated NSs have been estimated using different methods, namely from the spin-down law, cooling models, and kinematics. The method we propose in this study to estimate the true ages of these objects has only been applied, in its original form, to estimate the age of white dwarfs from their cumulative luminosity function in globular cluster (see for e.g. Goldsbury et al. (2012)). The method itself is purely...
a statistical one, for which the underlying assumption is that the objects in the sample follow a Poisson distribution (see for e.g. Felten1976) with a constant production rate. The important question to ask here is how good of an estimate of the true age is the statistical age. What is the inherent statistical error associated to this method of predicting ages? Consider the youngest object, RBS 1223, which is also the hottest among the eight isolated NSs. The kinematic age of RBS 1223 has been found based on its association to possible OB associations and young star clusters to be ~ 0.5 Myr (Tetzlaff et al.2010), although this age should only be regarded as the upper limit due to large uncertainties. The statistical age of RBS 1223 that we find in our study, given that the sample only contains eight such objects, is much smaller ~ 0.062±0.007 Myr, with uncertainties corresponding to systematic errors. The statistical error is of course much larger than the systematic one. Since the discovery of an object in a given volume follows Poisson statistics, the relative error scales as 1/√N where N is the sample size with ages t₁ ≤ t₂. Therefore, the error in the age of the first object is ±t₁ where t₁ is its statistical age. Likewise, the error in the age of the eighth object is ±t₈/√8. Evidently, one needs a much larger sample to reduce the statistical errors to that comparable to the systematic errors.

4 DISCUSSION

The ages of isolated NSs are primarily important for constraining their inner structure. In addition, they can be useful for accurately determining the birthplace of the object, if its proper motion is known. Similarly, if the SNR-NS association has been made, then the age of the object can reveal its space velocity and the kinematics of the SNR. The knowledge of ages of such objects is also useful for population synthesis models which rely on the spatial and velocity distributions, and the birthrates of NSs. In this study, we propose a statistical method to estimate the true ages of the ROSAT discovered sample comprising the M7. We then use the age estimates along with the derived spectral temperatures to compare the data with some cooling models. The strength of this technique, as discussed earlier, lies in obtaining a larger sample of coolers. With only eight objects, the statistical error is indubitably much larger.

The statistics can be improved by locating more of these objects in the disk of the Galaxy. In a recent population synthesis study, Posselt et al.2010 find that young isolated NSs, that are both hot and bright, with ROSAT count rates below 0.1 cts s⁻¹ (the ROSAT bright source catalog had a limiting count rate of 0.05 cts s⁻¹) should be located in OB associations beyond the Gould belt. They also remark on the possibility of finding new isolated cooling NSs by conducting yet another careful search of such objects in the RASS and using the recently published XMM-Newton Slew Survey (Esquej et al.2007). However, they note that ROSAT observations are incapable at locating the isolated sources with sufficient spatial accuracy, such that many optical counterparts can be found in its large positional error circle. On the other hand, although XMM-Newton is much more sensitive, albeit with strong inhomogeneities, and can probe deeper into the Galactic plane, the slew survey only covers 15% of the sky currently. Searching the RASS for new isolated NSs may appear to be a promising avenue, however, it is unlikely that any new sources will be identified. What is needed at the moment is another all-sky survey that is able to surpass ROSAT in both sensitivity and positional accuracy. In that regard, the upcoming eROSITA mission (Cappelluti et al.2011) shows a lot of promise, and its planned launch in 2014 makes it very timely. The X-ray instrument eROSITA will be part of the Russian Spectrum-Roentgen-Gamma (SRG) satellite, equipped with seven Wolter-I telescope modules with an advanced version of the XMM-Newton pnCCD camera at its prime focus. The telescope will operate with an energy range of 0.5 – 10 keV, a field of view (FOV) of 1.03°, an angular resolution of 28″ averaged over the FOV, and a limiting flux of ~ 10⁻¹⁴ erg cm⁻² s⁻¹ in the 0.5 – 2 keV energy range and ~ 3 × 10⁻¹³ erg cm⁻² s⁻¹ in the 2 – 10 keV energy range. The all-sky survey will reach sensitivities that are ~ 30 times that of the RASS where the entire sky will scanned over a period of four years.

### Table 1. Properties of nearby thermally emitting isolated NSs

| Object      | P (s) | D (pc) | T_{bb} (eV) | N_H (10²⁰ cm⁻²) | F_s | N_{OB} | τ (Myr) |
|-------------|-------|--------|-------------|-----------------|-----|--------|---------|
| RBS 1223    | 10.31² | 11.20² | ≥ 525³      | 118 ± 13        | 0.5 ± 2.1 | 4.5 | 3.839^+0.05^−0.05 | 0.014 ± 0.003 |
| 2XMM J104608.7+4 | - | - | 390 ± 430⁴ | 92 ± 15        | 4.6 ± 0.2 | 8.7 | 2.347^−1.32^+0.09^−0.04 | 0.15 ± 0.03 |
| RX J1065.3 + 3349⁵ | - | - | 325 ± 390⁶ | 86 ± 98        | 0.6 ± 1.5 | 1.15 | 0.631^+0.91^−0.10 | 0.13 ± 0.03 |
| RBS 1774⁷   | 9.437⁸ | 4.1 ± 1.8⁹ | 330 ± 170¹⁰ | 79 ± 4         | 1.3 ± 0.3 | 11.5 | 1.986^+0.247^−0.041 | 0.26 ± 0.03 |
| RX J0806.4 – 4123¹¹ | 11.37¹² | 5.5 ± 3.0¹² | 240 ± 25¹³ | 78 ± 7         | 2.5 ± 0.9 | 2.9 | 0.657^+0.022^−0.092 | 0.23 ± 0.03 |
| RX J0720.4 – 3125¹⁴ | 8.39¹⁵ | 6.98 ± 0.02¹⁵ | 330 ± 170¹⁶ | 79 ± 4         | 1.3 ± 0.3 | 11.5 | 1.986^+0.247^−0.041 | 0.26 ± 0.03 |
| RX J0420.0 – 5022¹⁷ | 3.45¹⁸ | 2.8 ± 0.3¹⁸ | 350¹⁹ | 57 ± 25        | 1.7 | 0.69 | 0.323^+1.033^−0.359 | 0.43 ± 0.17 |
| RX J1856.5 – 3754²⁰ | 7.06²¹ | 2.97 ± 0.07²¹ | 161²² | 57 ± 1         | 1.4 ± 0.1 | 14.6 | 0.597^+0.059^−0.045 | 0.52 ± 0.17 |

F_s (10⁻¹² erg cm⁻³ s⁻¹) - The absorbed X-ray flux in the ROSAT energy band (0.12 – 2.4 keV).

¹Schwope et al.1999,²Kaplan & van Kerkwijk2005,³Posselt et al.2007,⁴Pires et al.2004,⁵Motch et al.1999
⁶Posselt et al.2007,⁷Zampieri et al.2001,⁸Kaplan & van Kerkwijk2009,⁹Kaplan & van Kerkwijk2009
¹⁰Posselt et al.2007,¹¹Haberl et al.1998,¹²Zane et al.2005,¹³Kaplan & van Kerkwijk2009b
¹⁴Haberl et al.1997,¹⁵Kaplan & van Kerkwijk2005,¹⁶Kaplan et al.2007,¹⁷Haberl et al.1999
¹⁸Kaplan & van Kerkwijk2011,¹⁹Posselt et al.2007,²⁰Walter et al.1996,²¹van Kerkwijk & Kaplan2008
²²Kaplan et al.2007

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